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Description and Results of Furniture Fire Modules Within Fast (HEMFAST)

Mark Dietenberger

March 1987

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U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Fire Research
Gaithersburg, MD 20899

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Interim Technical Report,
July 1985 to July 1986

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Notice

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ABSTRACT

The Heat and Mass Transport of Furniture Fire, Smoke and Toxic Gases (HEMFAST) program simulated the furniture fire and the toxic gas growth in a room and its spread to the other rooms. This was achieved by incorporating an improved furniture fire model into the FAST model in current usage at NBS. The furniture fire model was designed to be self-controllable in simulating a fire source utilizing as inputs only the bench scale data of new scalable material burning rates, flame spreading, thermal ignition, and the flame properties of the following: soot volume fraction, C_2O and H_2O mass fractions of fuel weight, and gas temperatures. Since the Hottels' zoning method was used in the thermal radiation model it was possible to consider surface emissivities less than unity on all surface elements, and to consider three isothermal gray gas volumes which are the high-temperature flaming plume, the sooty upper gas layer, and the lower gas layer at 50% relative humidity. Some salient features are noted in the simulation of a sample fire growth on a furniture mockup.

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LIST OF SYMBOLS

- ρ_o = Surface layer density of fuel material (kg/m^3).
 C_o = Surface layer heat capacitance of fuel material ($\text{kJ/kg}^\circ\text{K}$).
 σ_o = Surface layer thickness of fuel material (m).
 ρ = Bulk density of fuel material (kg/m^3).
 C = Bulk heat capacitance of fuel material ($\text{kJ/kg}^\circ\text{K}$).
 μ = Extinction coefficient for radiative absorption (m^{-1}).
 T_e = Preheated virgin material temperature ($^\circ\text{K}$).
 T_{ig} = Thermal ignition temperature of fuel material ($^\circ\text{K}$).
 q_k = Incremental surface heat flux as defined in Fig. 1 (kW/m^2).
 s = Surface distance in normal direction from the flame front (m).
 V_p = Flame spread rate at flame front (m/s).
 $\dot{h}_i$ = Heat release flux measured by cone calorimeter (kW/m^2).
 $\dot{m}_i$ = Mass release flux measured by cone calorimeter (kg/sm^2).
 q_i = Net surface heat flux with $\dot{h}_i$ and $\dot{m}_i$ (kW/m^2).
 q_c = Surface convective heat flux (kW/m^2).
 q_{r_f} = Surface flame radiative flux (kW/m^2).
 T_b = Surface temperature of burning material ($^\circ\text{K}$).
 q_{r_i} = Cone calorimeter radiative flux (kW/m^2).
 q_o = Surface heat flux required to scale $\dot{h}_i$ and $\dot{m}_i$ (kW/m^2).
 G_i = Time stretching parameter for scaled time.
 Q_i = Total heat release of the test sample i (kJ/m^2).
 Q^* = Averaged total heat release of the test sample i (kJ/m^2).
 T^* = Scaled time (kJ/m^2).
 L = Heat of pyrolysis (kJ/kg).
 H = Heat of combustion (kJ/kg).

LIST OF SYMBOLS (continued)

- Q_c = Total heat release rate in plume (kW).
 ρ_∞ = Ambient air density (kg/m^3).
 C_p = Ambient air heat capacitance ($\text{kJ/kg}^\circ\text{K}$).
 T_∞ = Ambient air temperature ($^\circ\text{K}$).
 g = Gravitational acceleration (m/s^2).
 D = Hydraulic diameter of flame base (m).
 Q_D^* = Dimensionless pool heat release rate.
 Z_{fp} = Visible pool flame height (m).
 Z_w = Wall pyrolysis zone length (m).
 Y_w = Wall pyrolysis zone width (m).
 Q_w^* = Dimensionless wall heat release rate.
 Z_{fw} = Visible wall flame height (m).
 Z_f = Visible merged flame height (m).
 Z_{fr} = Solid flame height (m).
 T_f = Solid flame temperature ($^\circ\text{K}$).
 ϵ = Soot emissivity of flame.
 ϵ_g = Gaseous emissivity of flame.
 ϵ_f = Flame emissivity.
 κ = Soot extinction coefficient (m^{-1}).
 f_v = Soot volume fraction.

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SECTION 1

INTRODUCTION

A milestone has been reached in the development of a model which simulates the furniture fire and the toxic gas growth in a room and its spread to other rooms. This was achieved by merging an improved version of the Furniture Fire Model with the FAST program, a current multi-room fire model developed at NBS. The result is the Heat and Mass Transport of Furniture Fire, Smoke, and Toxic Gases (HEMFAST) computer program. The Furniture Fire Model has three important qualitative programming features. The first is that each main module was designed to be flexible, efficient, and modular. Secondly, each main module has made effective use of bench scale data such as the ignition and flame spread rate, the burning and constituent mass loss rates, and the thermal radiation properties of furniture samples. Third, each main module was able to fit into the specific areas in the FAST code, making it more likely that the HEMFAST modules will fit in other room fire models, such as the HARVARD CFC series. A high level flowchart for HEMFAST is shown in Appendix A and is an elaboration on these comments for specific modules.

The main modules of the Furniture Fire Model were described in the interim report, "Furniture Fire Model", Reference 1, and their high level flowcharts are reproduced in Appendix A. The Furniture Fire Model Demonstrator was described in the next interim report, "Mathematical Modeling of Furniture Fires", Reference 2, and was improved to obtain more realistic predictions of the fire growth and to prepare the model for merging with FAST. In the interim report a new model of thermal ignition and flame spreading was described and was applied to the demonstrator. In this work the application of the thermal ignition and the flame spreading models was refined to more accurately calculate the pre-ignition parameters such as the preheat temperature and the pre-ignition heat flux distribution located from the flame front out to the effective location of the preheat temperature. The module for the

Local Burn Rate, Fuel Consumption, and Convective Heat Flux Predictors (see Appendix A) was improved by considering the effect of net total surface heat fluxes on the local burn rate and the fuel consumption. This required the development of new scaling relationships for the data from the cone calorimeter for application to the furniture fire modeling. In the Flame Structure Model module, the conical frustrum was replaced by a polygonal based parallelepiped to more accurately represent the flame shape observed in video recordings of furniture fires conducted in the NBS Laboratory (Reference 3). The flame height modeling was also slightly modified. The approach to calculating the flame radiative properties is that of Bard and Pagni (Reference 4).

Examination of Version 17 of the FAST code and discussion with the NBS Center of Fire Research personnel indicated the FAST code needed two major improvements. The first was to insert a self-consistent fire source model in which the fire growth responds dynamically to its environment. The main response factors that need to be taken into account are the radiative feedback for controlling burn rate and flame spread, the air entrainment into the plume, and the air constituents concentration. The second major improvement was the extension of the Thermal Radiation Heat Transfer Analyzer module in the furniture fire model to a more detailed radiative heat transfer analysis of the room, including the effects of soot, carbon dioxide, and water vapor in the upper gas layer and of the water vapor in the lower gas layer. The air entrainment modeling seemed adequate in the FAST code itself. The only response factor not yet considered was that of reduced oxygen concentration in the lower gas layer as a result of its mixing with the upper gas layer. This response factor awaits the availability of the bench scale data of flame spread and burn rate due to varying ambient oxygen concentrations.

The resulting computer code is HEMFAST. Its input and results are described in the last section of this report. In particular, a generic situation of fire growth on a piece of furniture in a room with one opened window was reasonably simulated.

The furniture burnrate, the temperature profiles of the room and the gas layers, and the upper gas layer constituents concentrations are displayed as a function of time in Section 3.3 of this report. These predictions are qualitatively consistent with the furniture mockup tests in Reference 3.

SECTION 2

FURNITURE FIRE MODEL IMPROVEMENTS

The purpose of the improvements was to add more realism to the demonstrator version and to prepare the furniture fire model for incorporation to the FAST program. There are four main improvements covered in this section, which are: (1) the fine-tuning of the flame spread algorithms, (2) new computations of the local burn rate in response to varying surface heat flux, (3) a new flame shape algorithm, and (4) incorporation of radiative properties by Bard and Pagni. The modification of the thermal radiation analyzer module to take into account the room and the gas layers geometries is explained lastly.

2.1 FLAME SPREADING ALGORITHM IMPROVEMENTS

The flame spreading algorithm was improved by incorporating better interpretations of the flame spread rate equations in Reference 2. The flame spread rate formulae for thermally thick and thin materials are reproduced in a slightly modified form below.

Thermally thick limit, $\rho_o C_o \sigma_o + \rho c / \mu \rightarrow 0$, for PMMA:

$$V_P = \left(\frac{\sum_k q_k \sqrt{4 s_k / \pi}}{\sqrt{\rho c k} (T_{ig} - T_e)} \right)^2 \quad (1)$$

Thermally thin limit, $\rho c k \rightarrow 0$, for polyurethanes:

$$V_P = \frac{\sum_k q_k s_k}{(\rho_o C_o \sigma_o + \rho c / \mu) (T_{ig} - T_e)} = \frac{C}{T_{ig} - T_e} \quad (2)$$

That is, the preheat temperature, T_e , is no longer the surface temperature at ignition time due to the net surface heat fluxes other than the flame feedback heat flux. T_e is now defined as the

current surface temperature at some surface distance, s_e , from the flame front on the virgin material. This implied a different interpretation of the feedback heat fluxes to mean the net surface heat flux distribution between the flame front and the surface distance, s_e . This heat flux distribution is used in either flame spread rate formulae listed above by constructing q_k and s_k as shown in Figure 1, and using the appropriate summation. If the heat flux distribution is some well defined function of s , the summation can be converted to a convenient integral. This new interpretation of the flame spread rate formulae is significantly different than commonly encountered in the literature, but it was necessitated by the requirement for ease of application to modeling flame spreading in the furniture fire model.

The flame spread procedure used in the furniture fire model is illustrated in Figure 2. A furniture cushion panel is divided up into square-like surface elements and nine of elements are shown in the figure. The net surface heat flux and the surface temperature is computed as a function of time at the midpoint of each element. Thermal ignition is assumed to occur when the surface element temperature reaches the ignition temperature. Piloted ignition is assumed to occur when the program user selects the time and the location of ignition. Once ignition occurs at a location, a small octagonal burning area is constructed. Flame spreading is simulated by moving the vertices of the burning polygon in a normal outward direction over an incremental distance in an incremental time period. The preheat temperature, T_i , the preheat heat flux, q_i , and the preheat surface distance, s_i , corresponding to the burning polygon vertice, i , are selected in the following way. Each virgin surface element temperature and heat flux is extrapolated to the intersection of the flame spread direction vector and of the vector drawn through the surface element midpoint parallel to the appropriate polygon line segment, as illustrated in Figure 2. Several such intersections can occur on a single flame spread vector because there are several virgin surface elements. The intersection point closest to the vertice of the flame spread

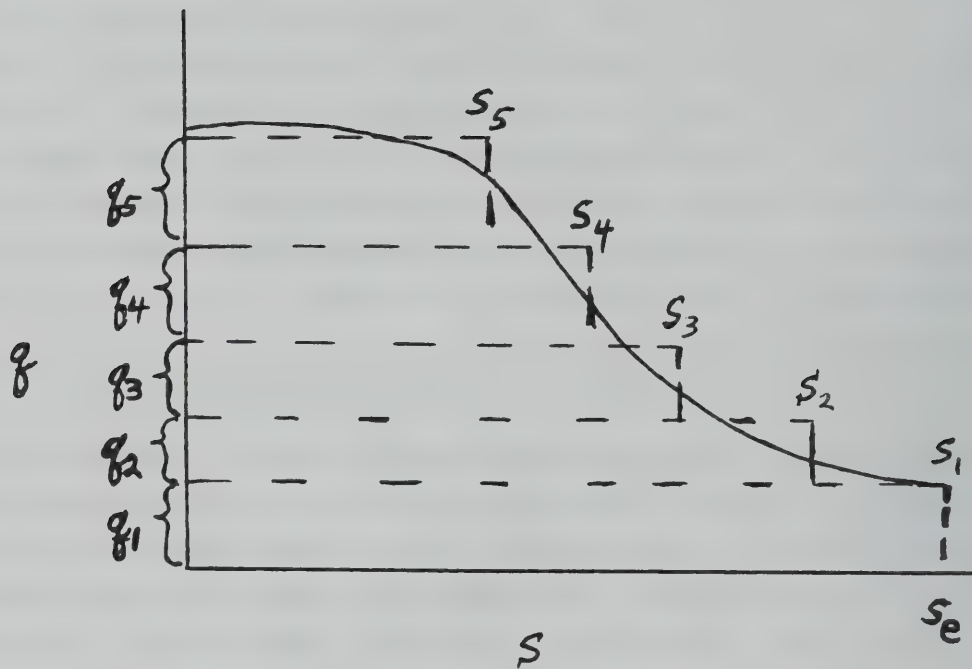


Figure 1. Construction of q_k and s_k from Heat Flux Distribution, $q = f(s)$, Fixed Ahead of the Flame Front at Speed V_p .

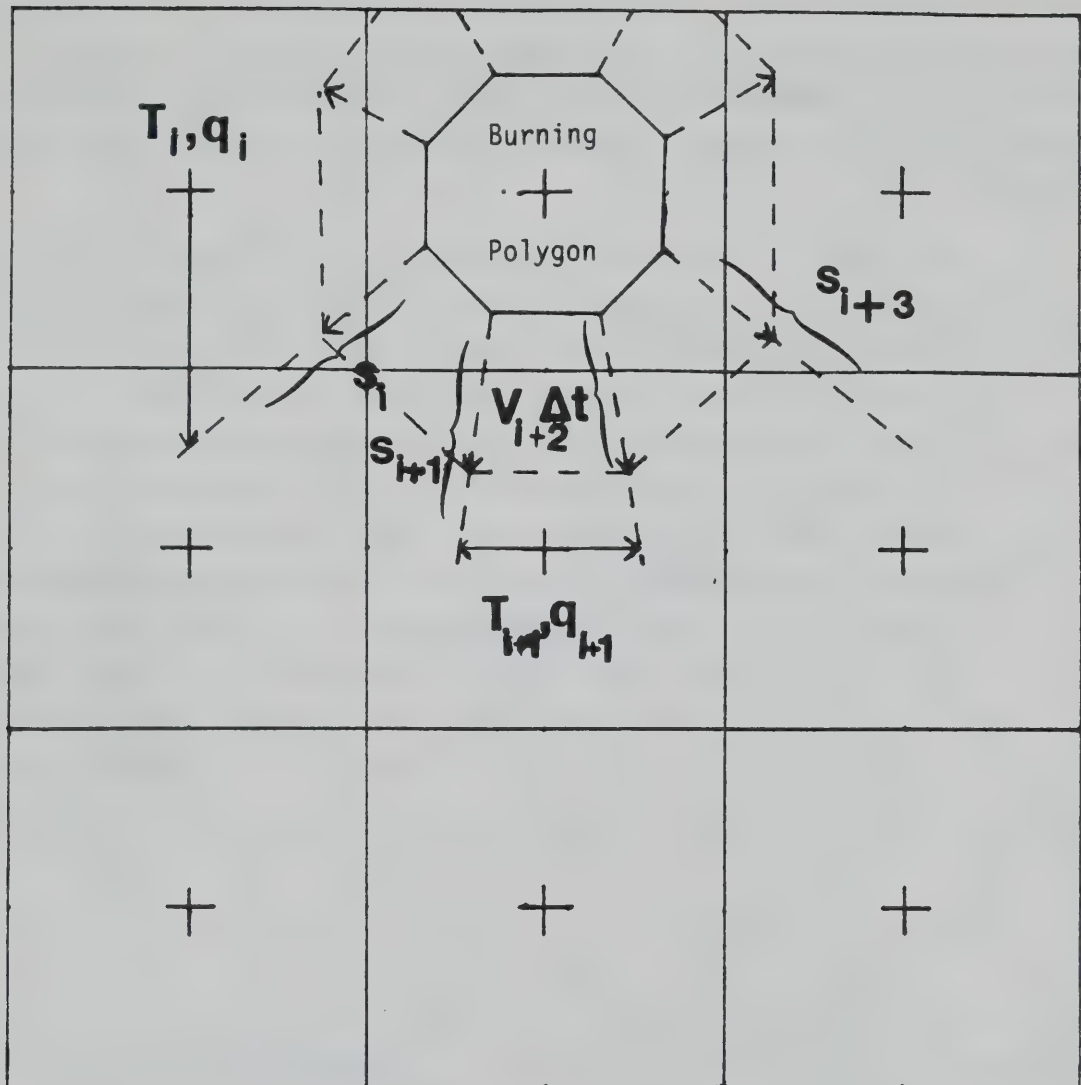


Figure 2. HEMFAST Flame Spread Procedure on a Heated Cushion Panel.

direction vector then determines the preheat surface distance, the preheat temperature, and the preheat heat flux. The closest burning surface element to the flame spread direction vector can similarly be found and the net surface heat flux of the chosen burning surface element is extrapolated to the burning polygon vertex.

Note the net surface heat fluxes can be decomposed into the radiative and the convective portions. The pre-ignitive heat flux distribution required for the flame spread rate formulae is constructed by fitting an exponential function between the radiative heat flux at the polygon vertex and the preheat radiative heat flux, and fitting a step function for the convective heat flux distribution. The convective heat flux distribution is different for opposed or assisting airflow, and so the appropriate boundary layer theory must be used. Other heat flux terms not accounted for, such as the flame foot convective/conductive heat flux or the glowing combustion/oxidative pyrolysis feedback heat flux, are treated as a constant to be curve fitted to the flame spread bench scale data. As a last comment, the flame spreading algorithm includes features to merge overlapping burning polygons, to keep spacings between polygon vertices at reasonable values, and to initiate flame spreading into adjoining cushion panels. An example of flame spreading simulated on a generic chair with a four cushion panel configuration divided into a total of 64 surface elements is shown in Figures 3 to 6.

2.2 NEW SCALING OF THE CONE CALORIMETER DATA

The Furniture Fire Model Demonstrator does not adjust the burning rate data from the cone calorimeter to account for varying irradiance levels, because the particular data used was only collected at a single irradiance level of 25 kW/m^2 . Also, there was no effective way to scale the burning rate data as a result of the varying net surface heat flux. In an effort to develop such a scaling relationship for the furniture materials tested in the cone calorimeter, a large series of the cone calorimeter database in the

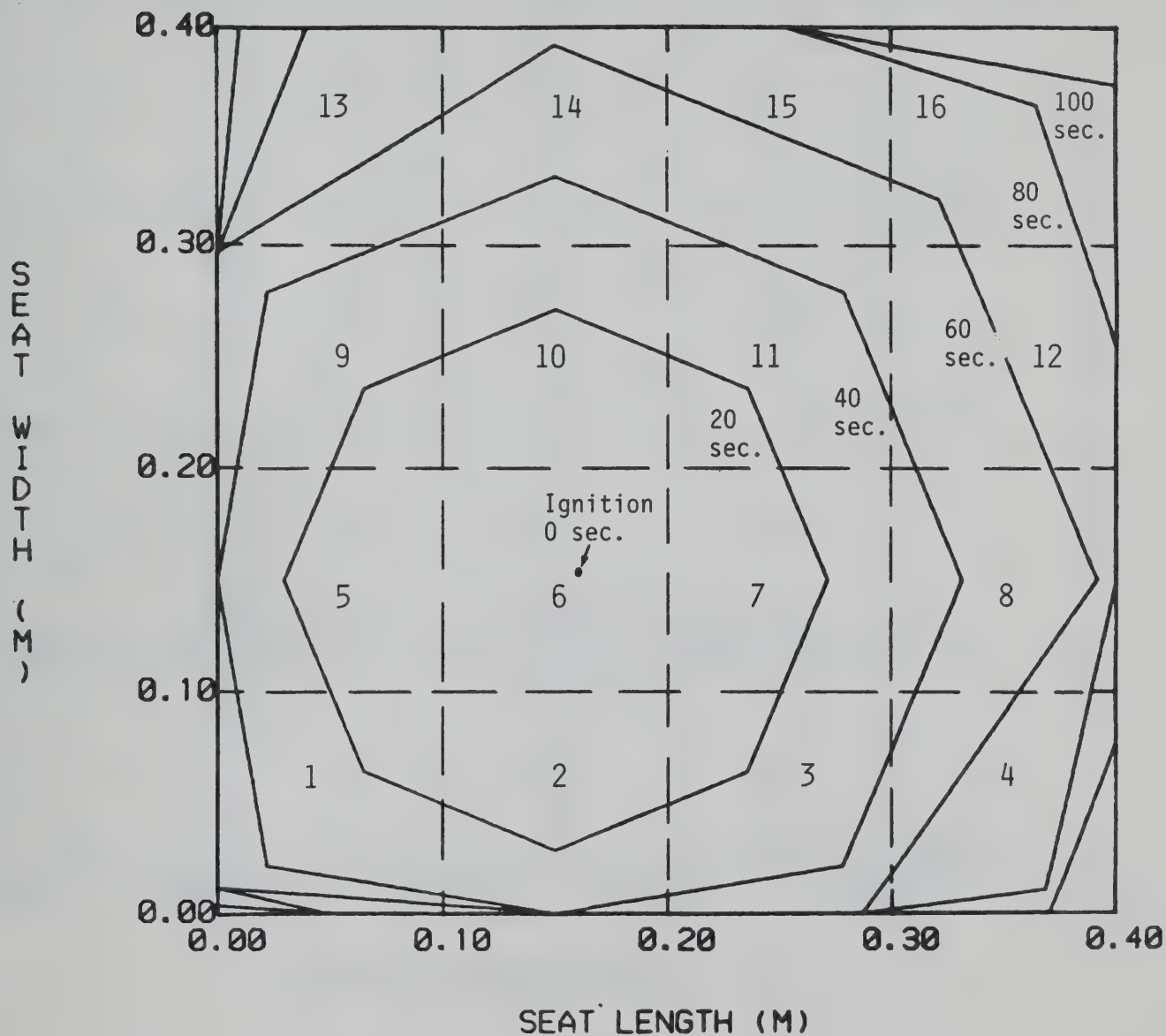


Figure 3. Example of Flame Spreading on Mockup Seat at 20, 40, 60, 80, and 100 Seconds on Surface Elements 1 to 16.

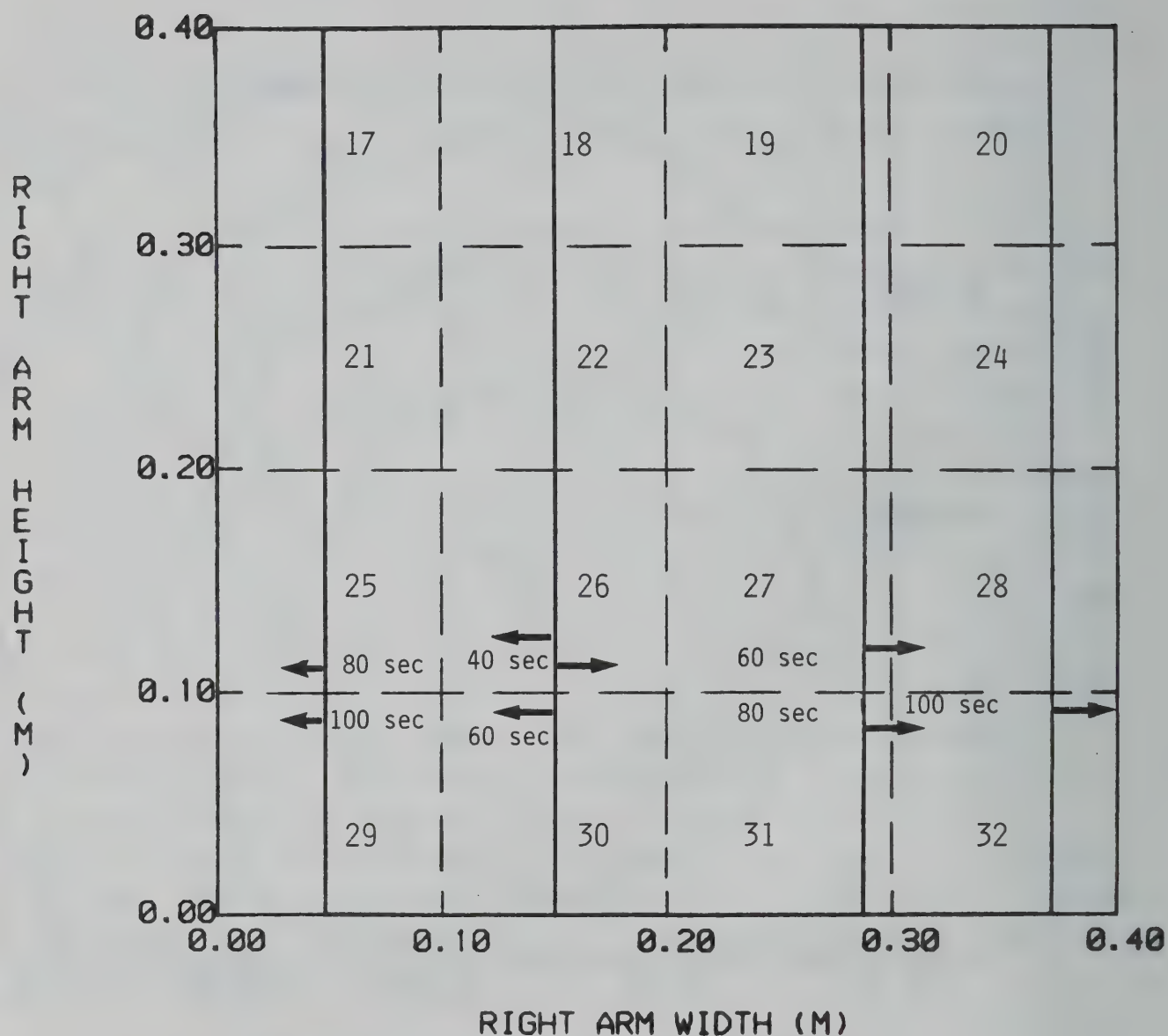


Fig. 4. Example of Flame Spreading on Right Armrest at 40, 60, 80, and 100 Seconds Simulation Time on Surface Elements 17 to 32. (This armrest begins burning near the center at 40 seconds and the flame spreads toward both edges. The flame spreading on the armrest is driven by the growth of the burning polygons on the seat cushion as these polygons intersect the armrest cushion. The dark lines in the figure show the flame positions at the times provided.)

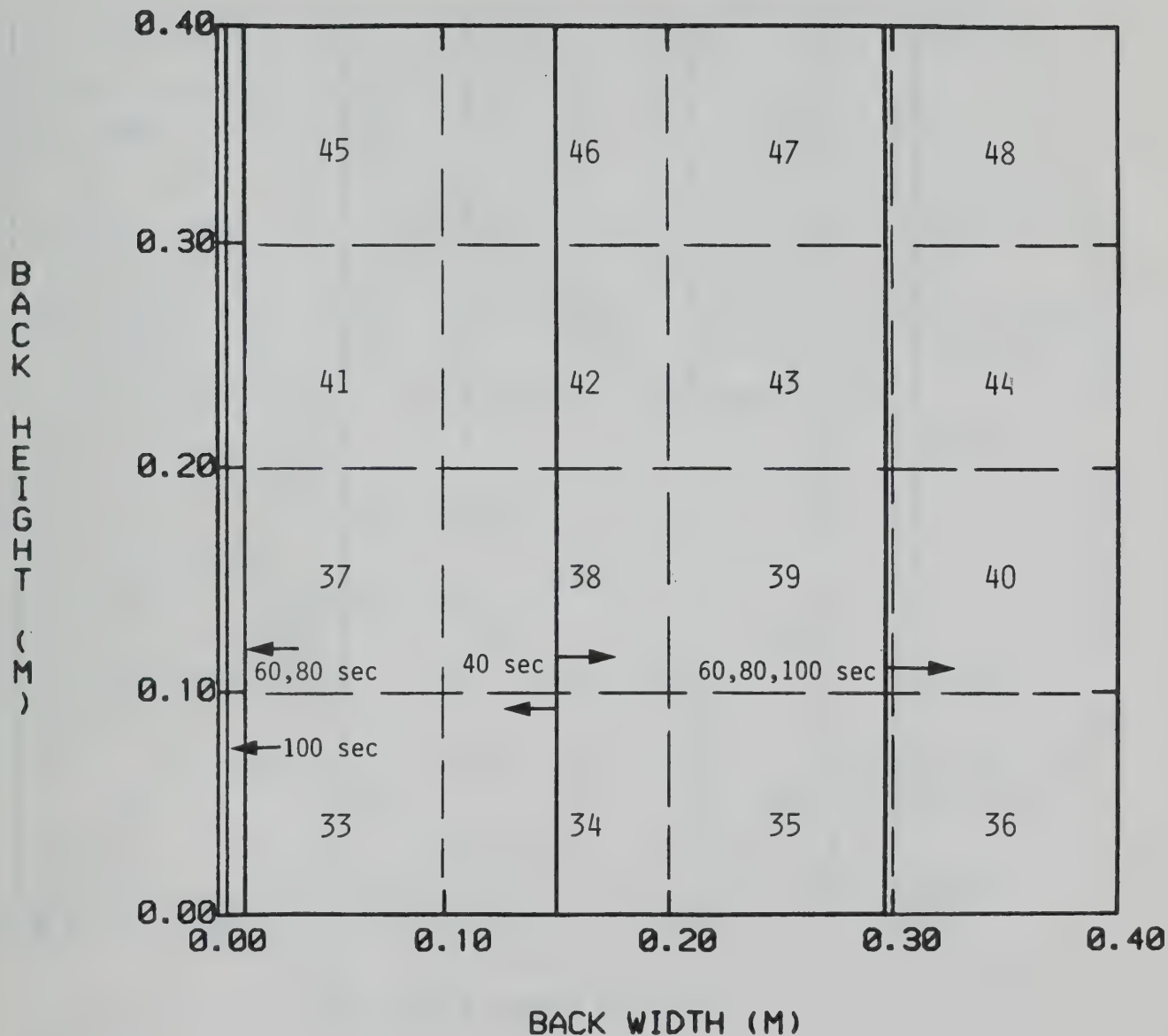


Fig. 5. Example of Flame Spreading on Backrest at 40, 60, 80, and 100 Seconds Simulation Time on Surface Elements 33 to 48. (This backrest begins burning near the center at 40 seconds and the flame spreads towards both edges. Flame spreading on the backrest is driven by the growth of the burning polygons on the seat cushion as these polygons intersect the backrest cushion. The dark lines in the figure show the flame positions at the times provided.)

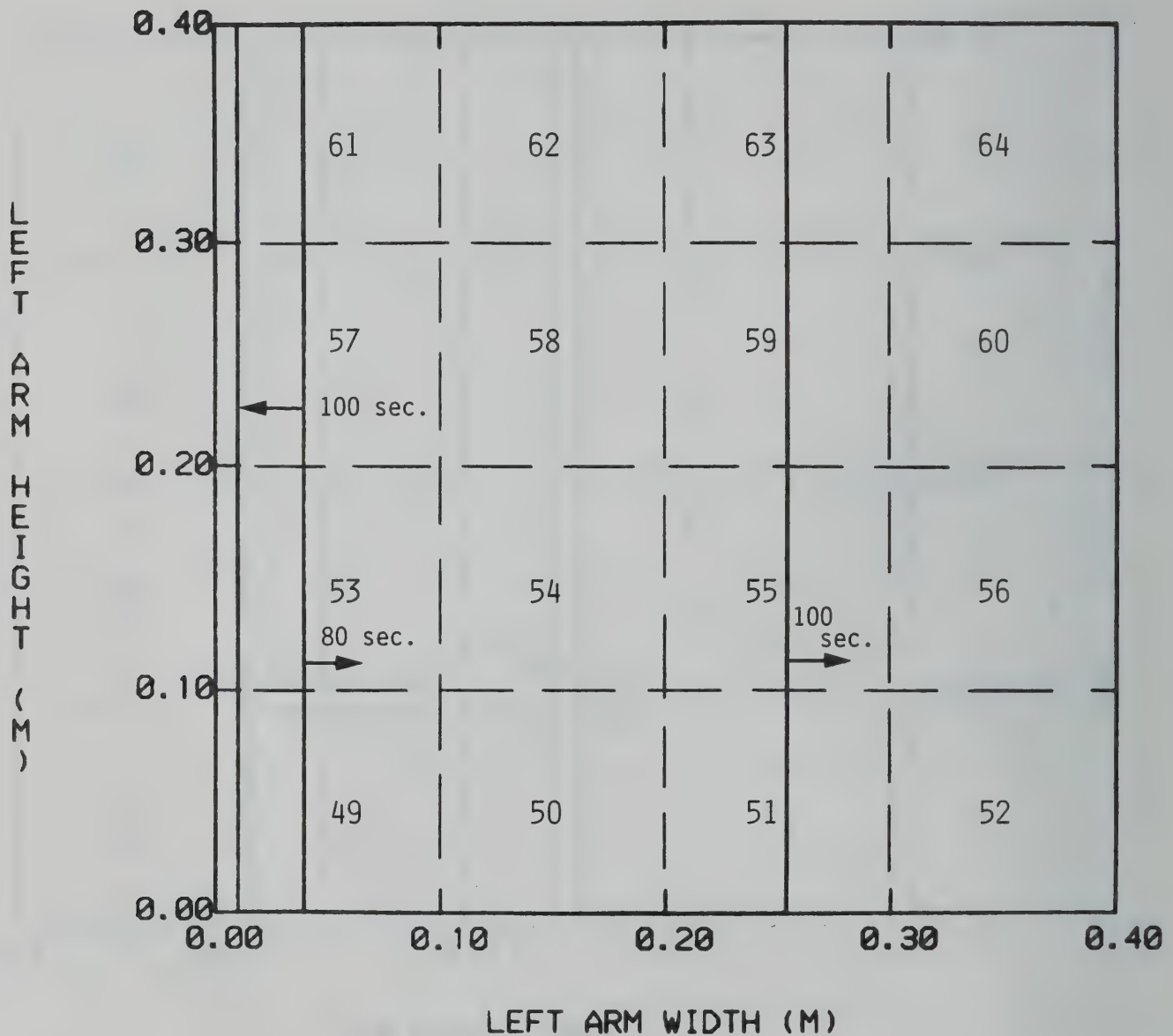


Fig. 6. Example of Flame Spreading on Left Armrest at 80 and 100 Seconds Simulation Time on Surface Elements 49 to 64. (This armrest begins burning near the left side at 80 seconds and the flame spreads toward both edges. Flame spreading on the armrest is driven by the growth of burning polygons on the seat cushion as these polygons intersect the armrest cushion. The dark lines in the Figure show the flame positions at 80 and 100 seconds.)

form of tabular output were obtained from John Krasny and Vito Babrauska (see References 3 and 5). This series included data corresponding to the following furniture materials: cotton fabric/treated PU foam, cotton fabric/non-treated PU foam, polyolefin fabric/treated PU foam, and polyolefin fabric/non-treated PU foam. These materials were subjected to cone calorimeter irradiances of 25, 30, 40, and 50 kW/m² during the tests. These 16 experimental runs were used to develop scaling relationships that allow us to use the concepts of heat of pyrolysis and the heat of combustion in the furniture fire model. The scaling relationships obtained are shown in the following.

Scaled heat release rate and mass loss rate:

$$\dot{h}^* = \left(\frac{q_o}{q_i + q_o} \right) \dot{h}_i \quad (3)$$

$$\dot{m}^* = \left(\frac{q_o}{q_i + q_o} \right) \dot{m}_i \quad (4)$$

where

$$q_i = q_c + q_{r_f} - \epsilon_s \sigma T_b^4 + q_{r_i} = \text{net surface heat flux} \quad (5)$$

corresponding with $\dot{h}_i$ and $\dot{m}_i$.

Scaled time is best defined by the heat release:

$$T^* = \int_0^{t_i} \dot{h}_i (1 + G_i) dt_i \quad (6)$$

where

$$G_i = \left(\frac{Q^* - Q_i}{Q_i} \right) \left(\cos \left[2\pi \left(\frac{\int_0^{t_i} \dot{h}_i dt_i}{Q_i} - 1/2 \right) \right] + 1 \right) \quad (7)$$

$$Q^* = \sum_{i=1}^n Q_i / n = \text{averaged total heat release of the test sample } i \quad (8)$$

$$T^* = Q^* \text{ at } \int_0^{t_i} \dot{h}_i dt_i = Q_i \quad (9)$$

The furniture materials are known to undergo glowing combustion or smoldering at low external irradiances, even when there are net surface heat flux losses. Here the net surface heat flux, q_i , is defined as the sum of the surface convective, the flame surface irradiant, the material surface radiant, and the external irradiant heat fluxes. These four surface heat fluxes can readily be calculated and their formulae are the same as the ones used in the furniture fire model. The surface convective heat flux, q_c , is calculated in the pool fire using the correlations by Orloff and deRis (Reference 6) and in the wall fire using the integral boundary layer model by Admah and Faeth (Reference 7). In both cases the surface convective heat flux is primarily sensitive to the material local mass loss rate, to the flame temperature and to the surface orientation. The flame surface irradiant heat flux, q_{rf} , is calculated using the mean beam length theory but with the same flame structure and the flame radiative properties as used in the furniture fire model. It is noted this irradiant heat flux is primarily sensitive to the burning rate, flame geometry and temperature, and to the maximum soot volume fraction in the flame. Since the burning material can be treated as a black-body (to a good approximation), the material radiant heat flux is assumed equal to the Boltzmann's constant times the fourth power of the burning temperature. The external irradiant flux, q_{ri} , is a measurable quantity in the cone calorimeter corresponding to the four irradiance levels. The surface heat flux, q_0 , from the glowing combustion at low irradiance levels (or accounting for an inaccurate burning temperature) is very difficult to measure or calculate, and so is treated as a fitting constant and is used as a basis to scale the heat release rate, $\dot{h}$, and fuel loss rate, $\dot{m}$, to the starred ordinates, $\dot{h}^*$, and, $\dot{m}^*$, respectively as indicated in above equations.

A term for the material surface conductive heat flux is not included because one of the purposes of scaling the burnrate data is to avoid a heat and mass transfer analysis within the material. For a surface burning at a constant rate on an ideal thermally thick material, a theoretical heat conduction solution with phase change gives the result that an imposed surface heat flux divided by the fuel loss flux is equal to the sum of the heat of pyrolysis and the material enthalpy increase up to the burning temperature. Whereas for a thermally thin material whose temperature is already near the burning temperature, the material enthalpy increase need not be considered along with the heat of pyrolysis. Thus for a thermally thick PMMA material and for a thermally thin paper the concepts of heat of pyrolysis and the heat of combustion are useful for scaling to any size fire. This is the motivation for creating a scaled heat release rate, $\dot{h}^*$, and the scaled fuel loss rate, $\dot{m}^*$, in the hope of collapsing the data onto a single point or a single curve.

For a composite furniture material that also can undergo charring, the effective heat of pyrolysis and the heat of combustion will change with the history of burning. Thus the scaled heat release rate and the scaled fuel loss rate will also change with the history of burning. Several researchers who have examined the curves of the heat release rate versus time for the different irradiances have attempted with some success to rescale the data as the heat release rate versus another abscissa variable, such as the amount of heat absorbed in the material, or the fuel loss, or the heat release as a function of time.

The variable corresponding to the heat absorption in the material was judged not applicable to this problem because of the additional complication of including the fitting parameter, q_0 . The fuel loss variable was also avoided because it seemed too sensitive to extra bulk materials not involved in combustion such as moisture and other vaporizing inert material. The heat release as a function of time is a more tolerant variable to the contaminants in the material. Also the total heat release of the same

material under differing conditions of irradiances and humidity tend more to be of a constant than the total heat absorbed or the total fuel loss. The furniture materials however cannot be constructed identically to each other, and furthermore, in real applications their foam thickness varies. Thus an additional scaling transformation must be applied to the heat release variable in order for the start-burn and the burnout points to be at the same value for similarly constructed materials under exposure to varying irradiances.

One approach would be to normalize the time changing heat release of the material i by dividing it by Q_i , the total heat release at burnout time and multiplying by Q^* , the averaged total heat release of similar materials. This effectively stretches (or shrinks) uniformly the time increments in the integral of the heat release rate. From intuitive considerations, however, there should be no stretching (or shrinking) of the incremental time intervals during the beginning phase of burning because the material behaves thermally like an infinitely thick translucent material with phase change, and also during the ending phase of burning because by then the material is thermally thin. Thus most of the stretching of time intervals should occur about halfway through the burning history. This is the reason for the cosine function of the normalized heat release history in the expression for G_i in the above equations. The amplitude of G_i is defined such that the scaled heat release (or scaled time or burn history), T_i^* , is the same as Q^* at burnout time for a constant value of the heat release rate. Since the heat release rate is not a constant, the scaled heat release at burnout time is actually a close approximation to the averaged total heat release of similar materials.

The plots of the scaled heat release rate versus the scaled time and of the scaled fuel loss rate versus scaled time are shown in Figures 7 to 14 for the four different furniture materials at four different irradiances. The optimum value for the fitting constant, q_0 , was 20 kW/m^2 for all four materials. All materials had in common the polyurethane foam, either treated or non-treated,

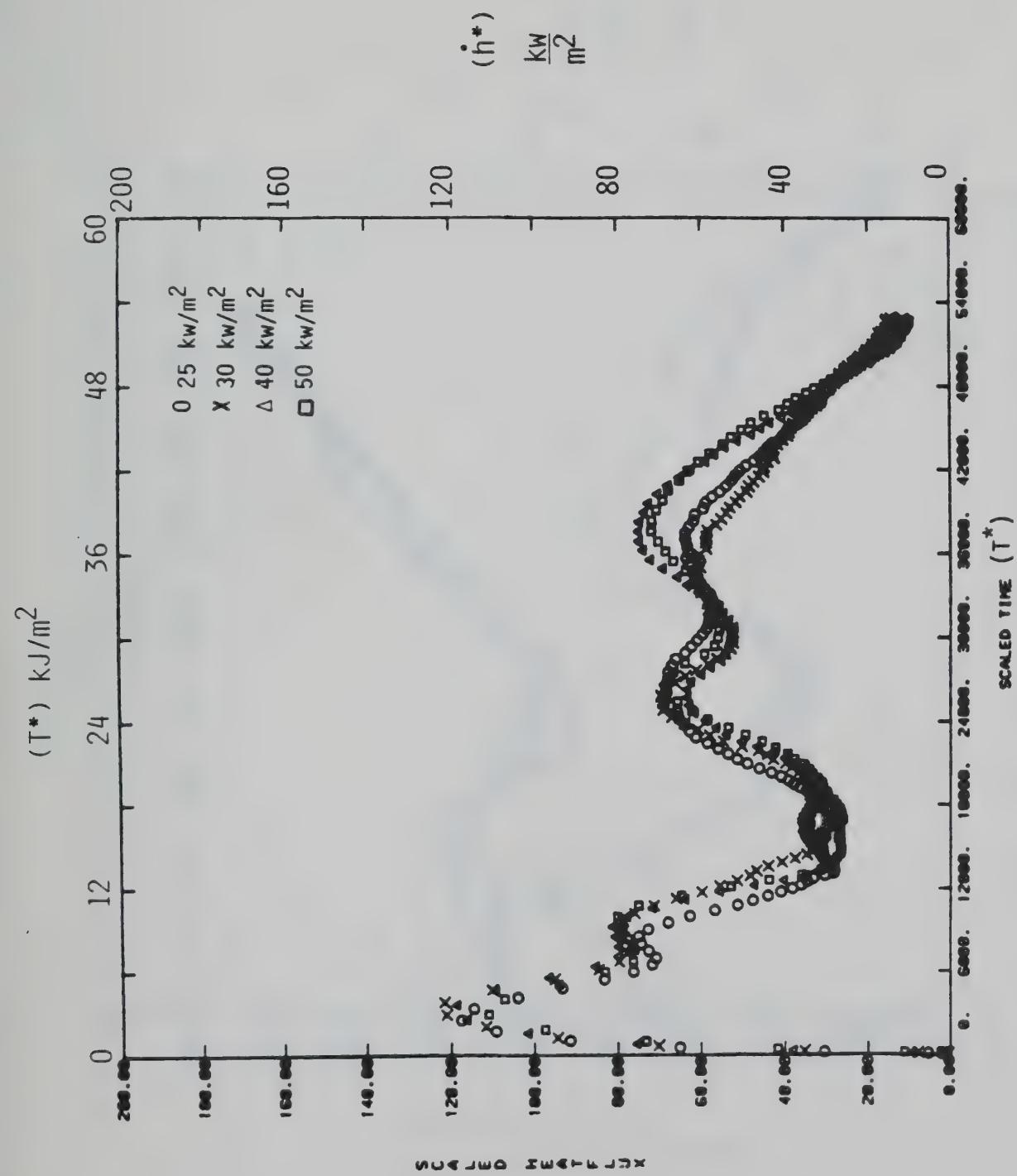


Fig. 7. Heat Rate Scaling for Cotton Fabric/Treated Foam

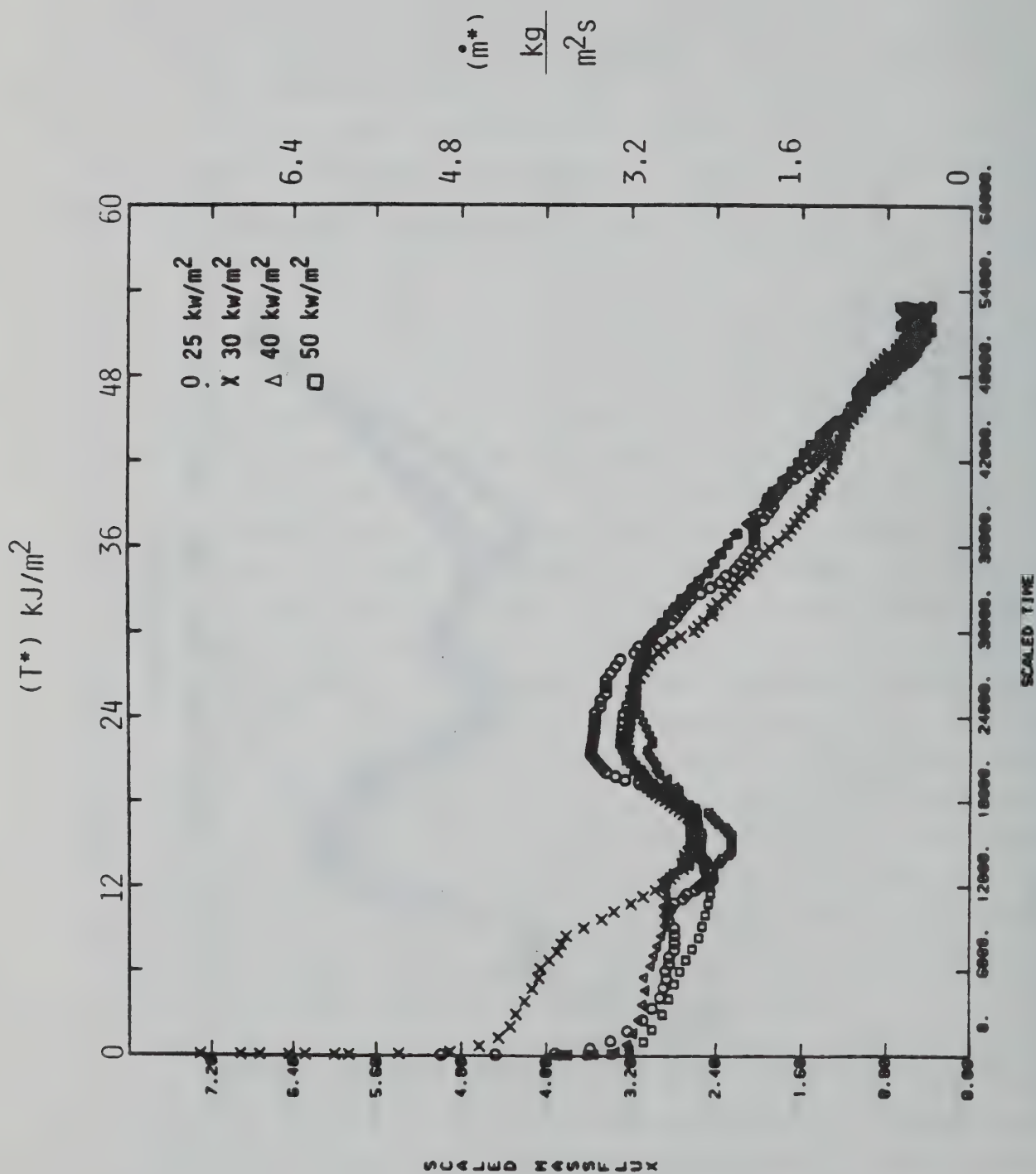


Fig. 8. Mass Rate Scaling for Cotton Fabric/Treated Foam

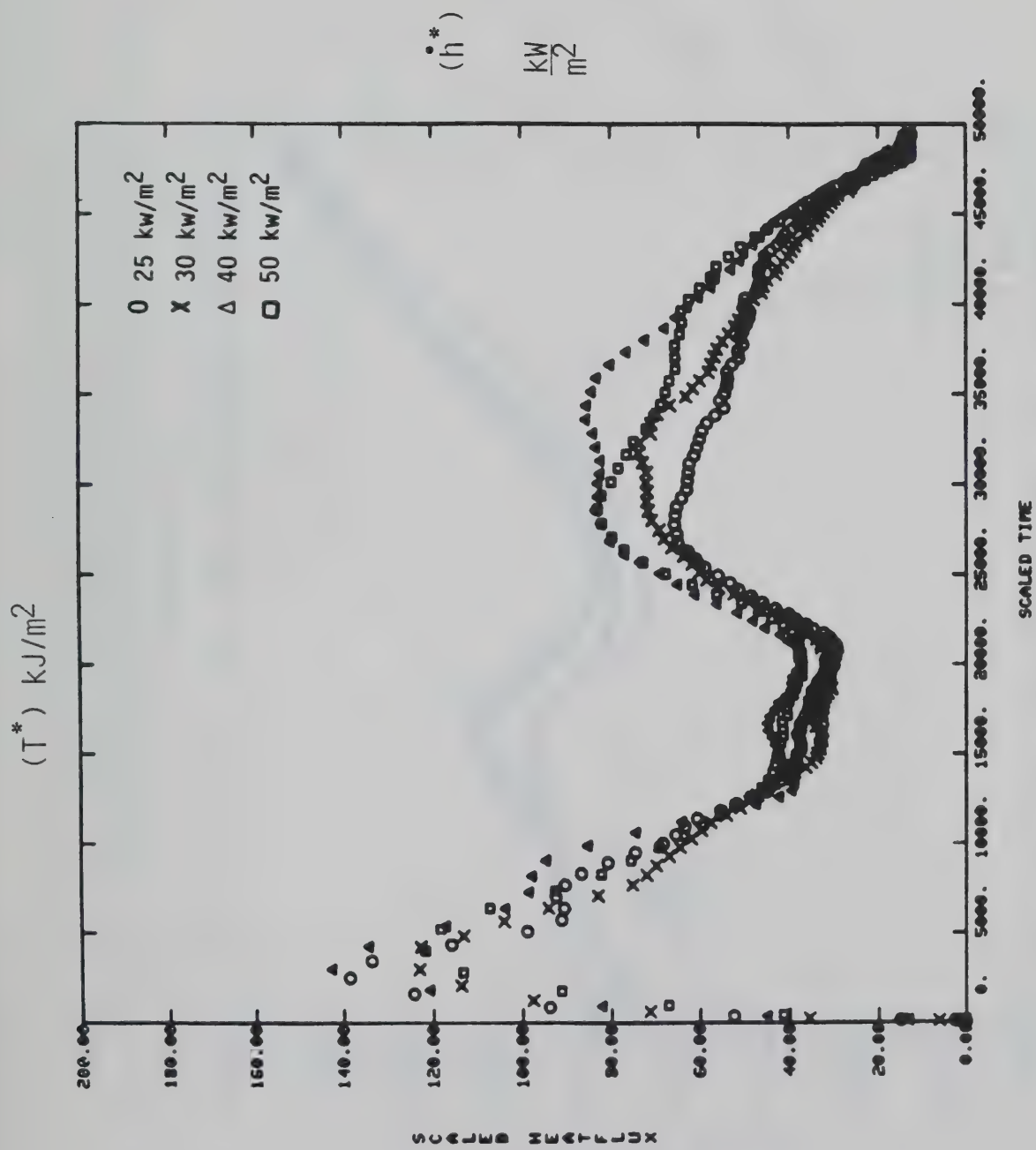


Fig. 9. Heat Rate Scaling for Cotton Fabric/Non-Treated Foam

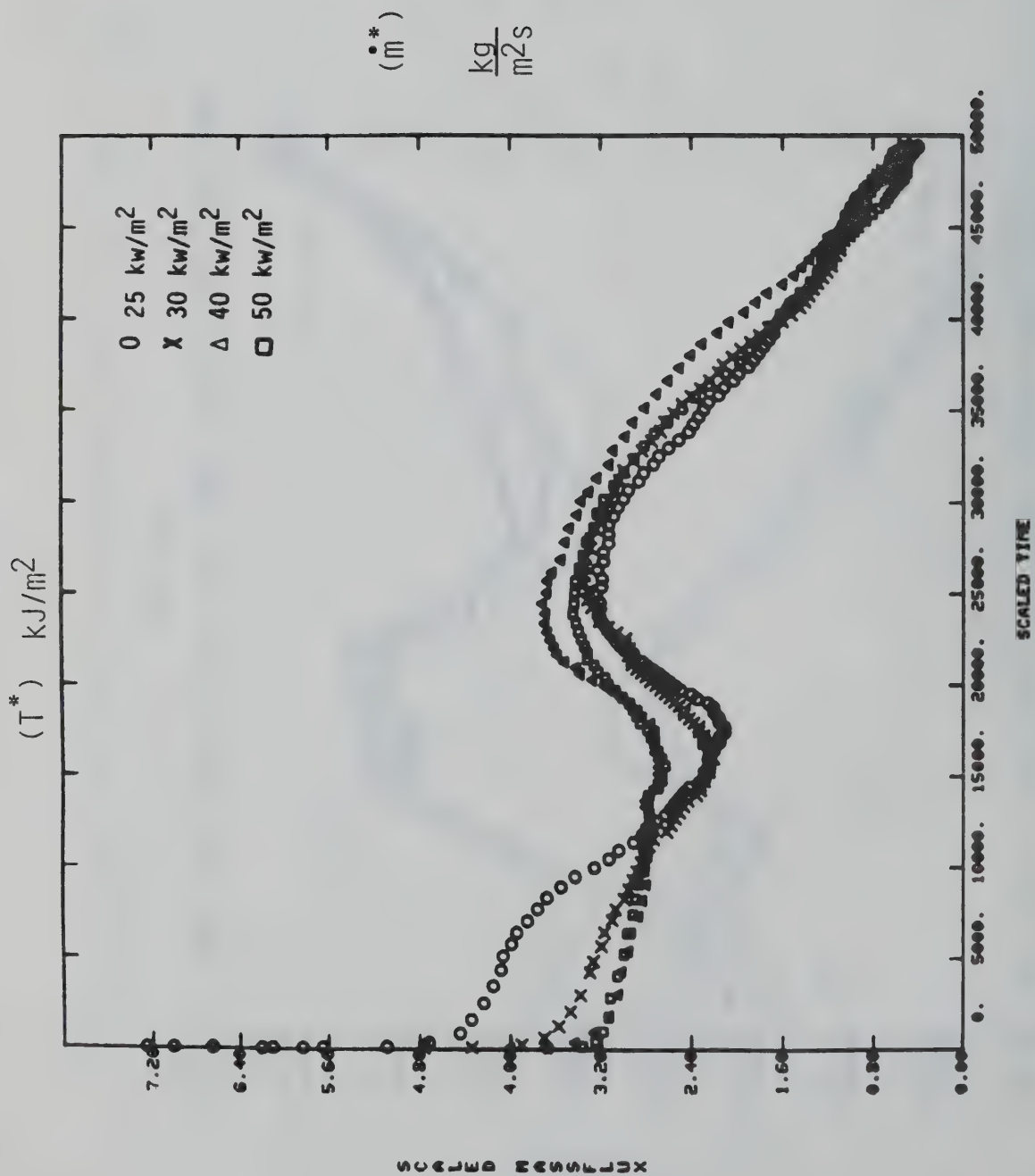


Fig. 10. Mass Rate Scaling for Cotton Fabric/Non-Treated Foam

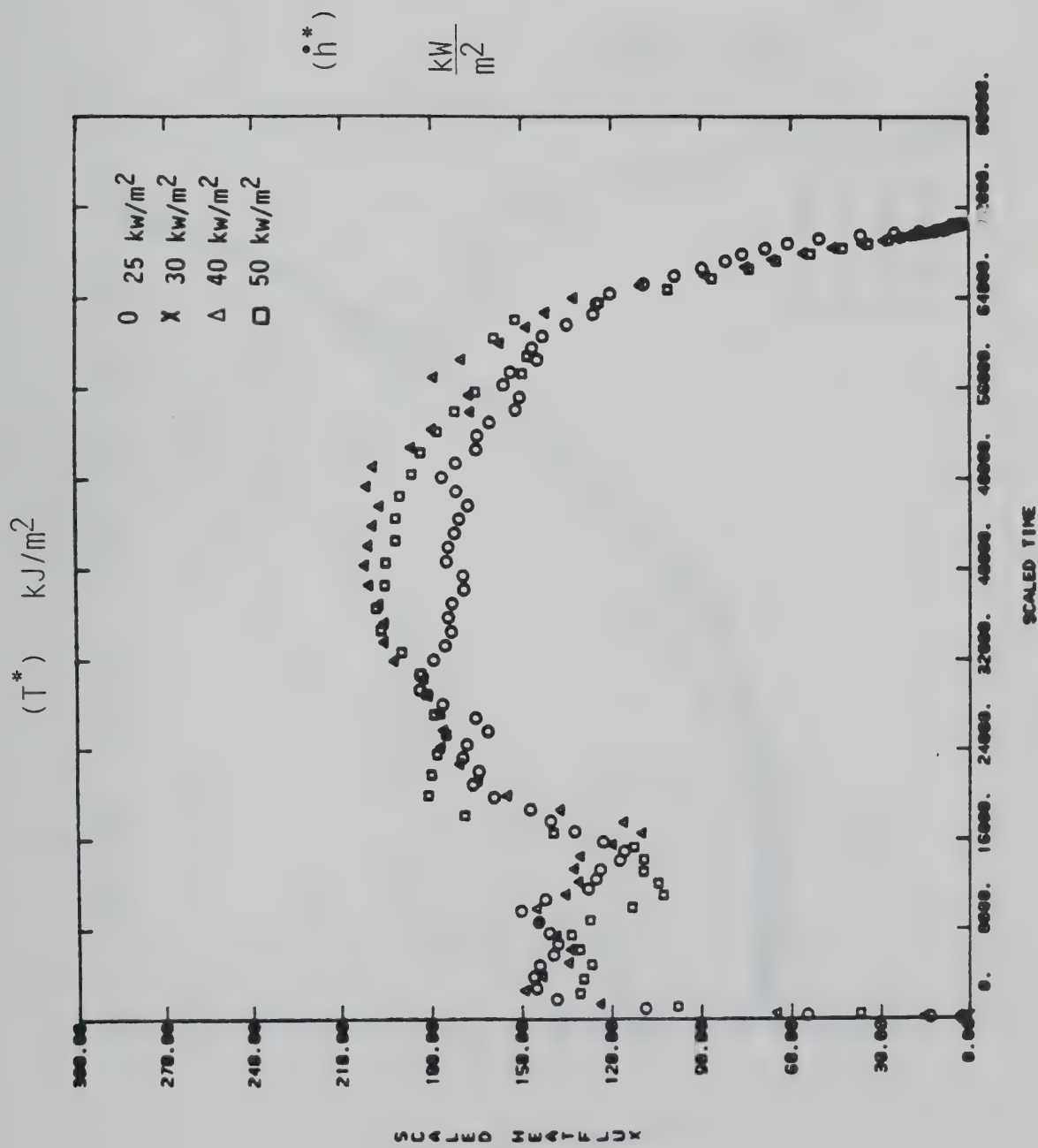


Fig. 11. Heat Rate Scaling for Polyolefin Fabric/Treated Foam

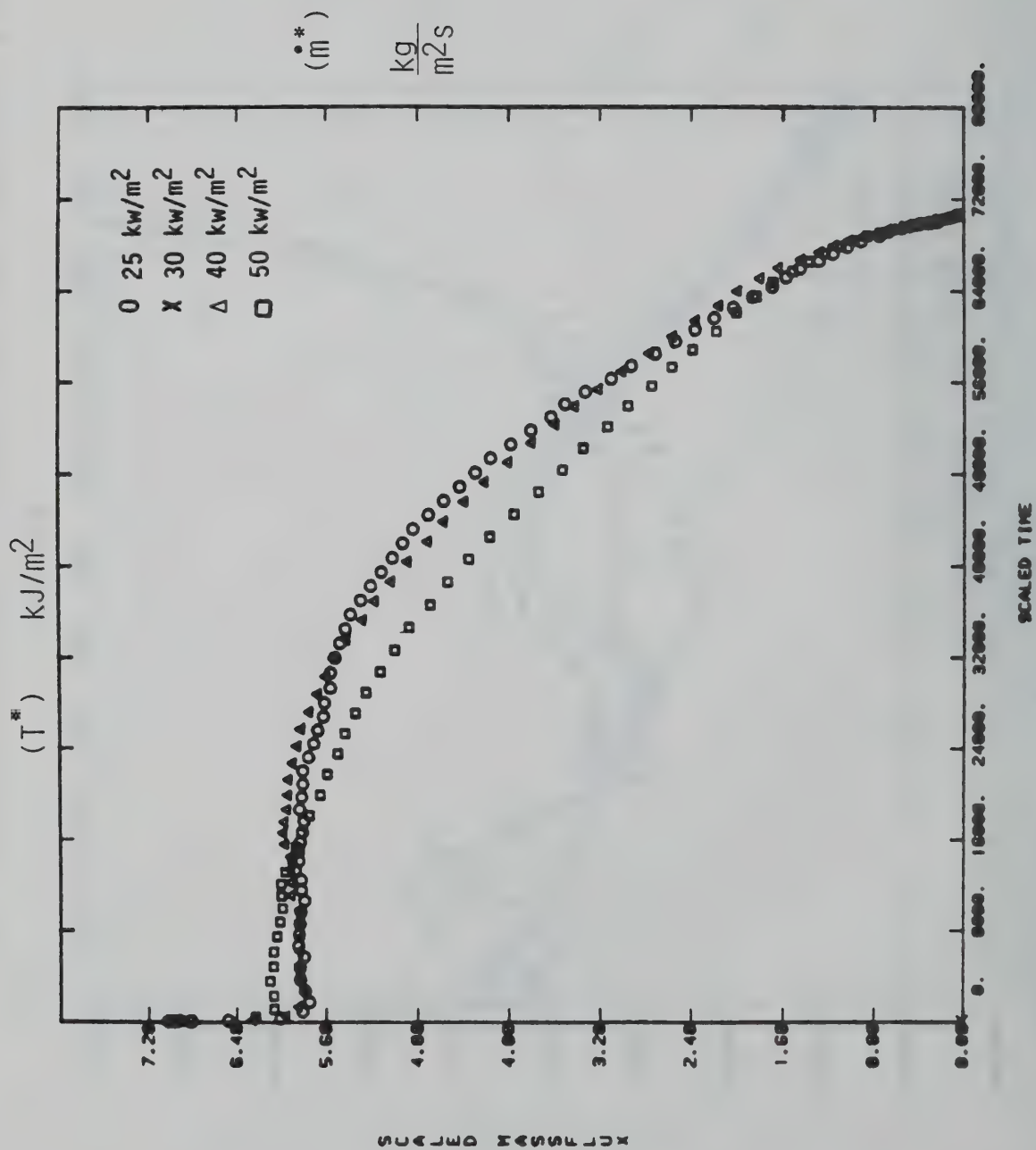


Fig. 12. Mass Rate Scaling for Polyolefin Fabric/Treated Foam

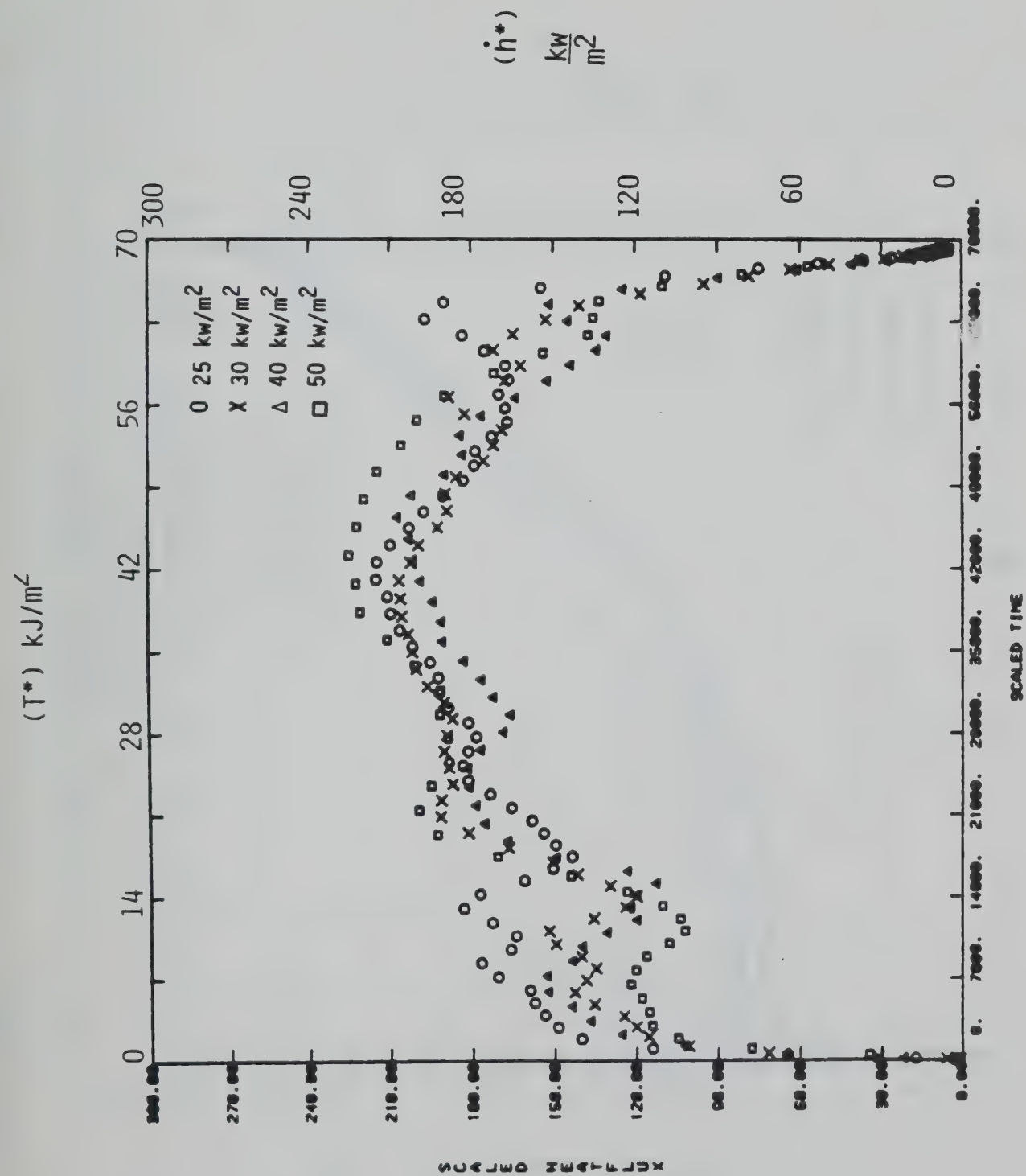


Fig. 13. Heat Rate Scaling for Polyolefin Fabric/Non-Treated Foam

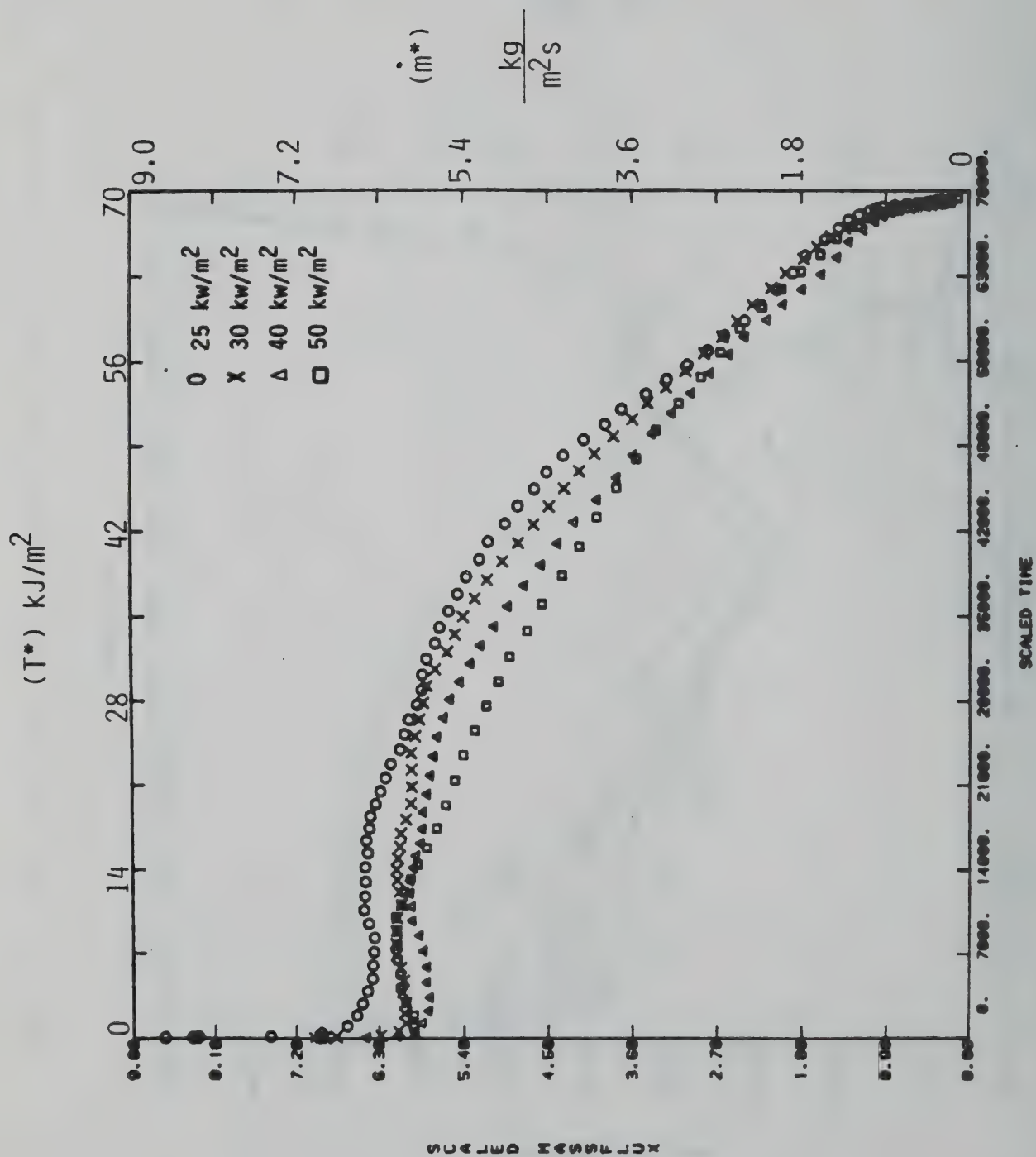


Fig. 14. Mass Rate Scaling for Polyolefin Fabric/Non-Treated Foam

and either with cotton fabric or polyolefin fabric. The fact the foam can still sustain a fuel loss under glowing combustion conditions even with a net surface heat flux loss, gives credence to the idea that q_o is mainly the surface heat flux due to the glowing combustion or oxidative pyrolysis. We thus have a feature, not available in several published scaling relationships, for a smooth transition from a glowing combustion state to a flaming combustion state in scaling with q_o .

In each of Figure 7 to Figure 14 the curves of the four irradiance levels effectively collapse to a single curve. The data points coalesce especially well in the beginning and the ending part of the burn history in each curve, thus supporting the reasonable assumptions made in formulating the time stretching parameter, G_1 . In summary, the utilization of a fitting parameter, q_o , and of the time stretching parameter, G_1 , was effective in collapsing the data at different irradiances to a single curve. Since these parameters were also based on a physical principle, although not in a rigorous fashion, we can interpolate and extrapolate to a certain extent from the scaled burnrate database as a function of the net surface heat flux and burn history. More specifically, by rearranging the scaling relationships in Equations (3) to (9) and noting the results in Figures 7 to Figure 14, it is still possible to define a heat of pyrolysis as a function of scaled time and define a heat of combustion also as a function of scaled time as shown in Equations (10) and (11) below.

Heat of pyrolysis is function of T^* only:

$$L(T^*) = \frac{q_o}{\dot{m}^*} = \frac{q_i + q_o}{\dot{m}_i} = \frac{q_{net} + q_o}{\dot{m}} \quad (10)$$

Heat of combustion is function of T^* only:

$$H(T^*) = \frac{\dot{h}^*}{\dot{m}^*} = \frac{\dot{h}_i}{\dot{m}_i} = \frac{\dot{h}}{\dot{m}} \quad (11)$$

for polyurethane:

$$q_o = 20 \text{ kW/m}^2$$

$$T_b = 700^\circ\text{K}$$

This approach gives us more confidence to interpolate and extrapolate from the cone calorimeter burning data at different irradiances to a time changing burn rate of a furniture surface element. More burnrate databases are being incorporated into the computer files in order to more severely test the scaling relationships.

2.3 FLAME STRUCTURE MODELING IMPROVEMENTS

Both the flame shape and the flame properties were changed in the flame structure module as a result of new information. The changes in this module did not affect the other main modules because of the geometries chosen for the furniture fire model. Each furniture cushion panel can have several burning surface elements, each having its own fuel loss and heat release rates as a function of burn history, and the panel can also have a few burning polygons which represent the flame spreading process. The cushion panel is a quadrilateral plane which can have any position or orientation in a three dimensional space. Four such cushion panels are combined to construct a generic chair. A rigorous three-dimensional vector analysis was utilized to represent the geometries of the furniture, flame, and the room for the reasons of flexibility, compactness, and efficiency. Thus it was quite easy to replace the conical frustrum flame shape used in the demonstrator version by a polygon-based parallelepiped shape shown in Figure 15. The new shape was decided after our recent viewing of the VCR recording of the furniture mockup fire tests at NBS.

Each flame shape is sub-divided into surface elements. Each surface element on the chair, the flame, or the room is characterized by its three-dimensional position vector, the element normal vector, and the element area. These characterizations are

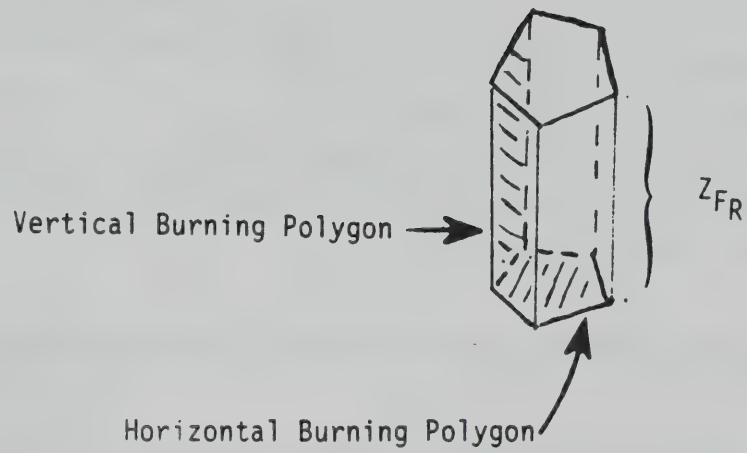


Figure 15. Flame Shape is a Polygonal-Based Parallelepiped.

used in the thermal radiation analysis to calculate the viewfactors and the Hottel exchange areas between all surface elements. The mean beam length approximations utilized in the Hottel exchange areas required computations of the flame volume, the flame surface area, and the burning polygon centroids, areas, and circumferences. The three dimensional vector analysis is used to obtain these geometric parameters. The mean beam length approximations also implied the use of the flame properties of soot and gaseous extinction coefficients and of the flame temperature, which are assumed spatially uniform inside a flame shape. This is consistent with the formulae presented for the flame properties by Bard and Pagni (Reference 4). The flame height formulae are presented in Equations (12) to (15) below.

Cetegen, et. al., formula for averaged visible pool fire height is,

$$Z_{fp}/D = \begin{cases} 3.3 (Q_D^*)^{2/3} & ; Q_D^* < 1 \\ 3.3 (Q_D^*)^{2/5} & ; Q_D^* > 1 \end{cases} \quad (12)$$

where

$$Q_D^* = (Q_c / [\rho_w c_p T_w g^{1/2} D^{5/2}])$$

D = hydraulic diameter

Q_c = total heat release rate.

Hasemi's formula for averaged visible wall fire height is,

$$Z_{fw}/Z_w = \begin{cases} 6.0 (Q_w^*)^{4/5} & ; Q_w^* < 1 \\ 6.0 (Q_w^*)^{2/3} & ; Q_w^* > 1 \end{cases} \quad (13)$$

where

$$Q_w^* = (Q_c / [\rho_\infty C_p T_\infty g^{1/2} z_w^{3/2} Y_w])$$

z_w = pyrolysis zone length

Y_w = pyrolysis zone width

Interpolation for merged flame:

$$z_f = z_{fp} \left(\frac{Q_{cp}}{Q_c} \right) + z_{fw} \left(\frac{Q_{cw}}{Q_c} \right) \quad (14)$$

where

Q_{cp} = heat release rate from horizontal surfaces

Q_{cw} = heat release rate from inclined surfaces

with a solid flame height:

$$z_{fr} = 0.4 z_f \quad (15)$$

The Cetegen, Zuboski, and Kubota's formula (Reference 8) for the averaged visible pool fire height was used for the conical frustrum flame shape in the Demonstrator version. This formula is also used in the upgraded Flame Structure Module along with Hasemi's recent formula (Reference 9) for the averaged visible wall fire height. It is noted the pool fire height is sensitive to the total heat release rate and to the hydraulic diameter of the flame polygonal horizontal base, while the wall fire height is sensitive to the total heat release rate and to the length and width of the inclined burning polygon. The effect of the flame radiative fraction on the flame height is considered minor and is not included at this stage. However, if both the seat and the back rest on the furniture are burning, an interpolation between the pool and the wall fire

heights is required and is given by Equation (14). The linear interpolation weights the pool fire height with the heat release rate from horizontal surfaces and weights the wall fire height with the heat release rate from inclined surfaces. The resulting visible height of the furniture flame shape is further reduced by sixty percent to obtain the 'solid' flame height defined in the above two references.

2.4 THERMAL RADIATION ANALYZER MODULE

Improvements in the flame properties module were mainly in the calculation of the soot and gas extinction coefficient and the corresponding flame emissivity. Using the results from Bard and Pagni (Reference 4) for radiation from soot and gas for any size pool fire, the inputs needed are the maximum soot volume fraction, the partial pressures of water and carbon dioxide gases, the mean beam length, and the flame temperature to calculate the extinction coefficient as given by Equations (16) to (23) below.

Bard and Pagni's scaling relationship for flame properties of pool fires:

$$\dot{q} = \epsilon_f \sigma T_f^4 \quad (16)$$

$$\epsilon_f = \epsilon + \epsilon_g - \epsilon \epsilon_g \quad (17)$$

$$\epsilon = 1 - \exp(-\kappa L) \quad (18)$$

$$\kappa = 36\pi F_a(\bar{\lambda}) f_v / \bar{\lambda} \quad (19)$$

$$\bar{\lambda} T_f = 0.40 \text{ cm}^\circ\text{K} \quad (20)$$

$$f_v / f_{v_{\max}} = 1.5 (\kappa L)^{1/3}, \quad \kappa L \leq 0.3, \quad (21)$$

$$f_v / f_{v_{\max}} = 1, \quad \kappa L \geq 0.3$$

For polyurethane, they obtained:

$$f_{v_{\max}} = 0.89 \text{ ppm} \quad (22)$$

$$T_f = 1200^\circ\text{K} \quad (23)$$

The soot extinction coefficient is a function of a particular mean wavelength and of the soot volume fraction. The mean wavelength is inversely proportional to the gas radiative temperature. The soot volume fraction reaches a saturation level for a large enough pool fire. For these reasons the model for the soot and gas extinction coefficient for the upper gas layer in the FAST model was also examined. The flame temperature of the pool/wall fire was assumed to be at 1200° Kelvin and the maximum soot volume fraction was taken to be 0.89 ppm. as corresponding to polyurethane foam materials.

Once again a main advantage of the furniture fire model is the flexibility in being able to completely revise any particular main module listed in Appendix A without affecting the other remaining modules. The freedom to choose any particular flame shape and to use a realistic flame property data is a result of relying on efficient computations of viewfactors between all surface elements as a basis for evaluating the Hottel's exchange areas between the furniture, room, flame, and the gas layers. As the surface elements are made smaller and as the flame approaches the optically thick limit, the radiative heat transfer approaches the theoretical solution on a sufficiently large computing facilities. Yet the furniture fire model is capable of running on a advanced personal computer without the surface elements becoming too big for a significant loss of accuracy. To allow this flexibility in adaptation to a computer facility the user can provide inputs to the geometrics of the model to control, (a) surface element size, (b) the resolution and the number of burning polygons, and in a later version (c) constructions of furniture shapes and multiple flame shapes.

SECTION 3

HEMFAST CODING DEVELOPMENT AND RESULTS

The emphasis during this contract period was on the inclusion of the furniture fire model into the model for the Transport of Fire, Smoke, and Toxic Gases (FAST) program. The flowchart for the main modules of HEMFAST are located in Appendix A. All modules shown were developed at UDRI except for the FAST model. Extensive modification of the thermal radiation and the fire source modelings in FAST were performed to accomplish this task. The flowchart of each module of the furniture fire model is also included in Appendix A. Each furniture fire main module has as input the processed bench scale data. These data are described in the following paragraphs. The merged program is now identified as the Heat and Mass Transport of Furniture Fire, Smoke, and Toxic Gases.

A magnetic tape copy of the HEMFAST program and its input file was submitted to NBS. A hard copy of the sample run was also provided. The computer programmer's comments and suggestions on executing the HEMFAST program on a CDC Cyber, such as the one at NBS, are located in Appendix B.

3.1 DISCUSSION OF FAST MODEL

The FAST model is a room model developed and presently used at NBS Center of Fire Research. The model employs mass flow zone modeling of smoke, soot, and molecular constituent movements in a multi-room configuration. The model presently has a diathermious, two-layer, and gray gas formulation of the radiative heat flux taken from Engel and Howell (Reference 10). The 3-D Hottel zoning formulation presently used in the furniture fire model was easily extended to the room environment by appropriate geometrical modifications in the computer program. Thus it was possible to calculate the radiative heat flux inputs for the four room boundaries: ceiling, upper wall, lower wall, and the floor, to the time dependent heat conduction solution of the surface temperature.

The FAST model presently uses as input, data from a gas burner or other fire source measured in the laboratory. Therefore, the model validation of FAST is limited to a few particular laboratory experiments until a self-consistent fire source model is developed. The incorporation of the furniture model into FAST was a way of providing such a self-consistent fire source.

Version 17 of FAST was sent to UDRI in December 1985. This version was modified for incorporating the furniture fire model. Examination of the FAST code revealed that only seven subroutines of the FAST model required modification. Six of the subroutines are called by the seventh subroutine, named SOURCE. There is a block of approximately 30 lines of code in SOURCE that pertain to the radiative heat flux and the furniture fire models alluded to earlier. Instead of replacing this block of lines in the SOURCE subroutine, we developed an optional bypass routine with a similar number of lines of code that will call the furniture fire model and call the extended 3-D radiative heat flux model to take into account the upper gas layer, the fire source, and the geometrical arrangement of the furniture and room in one set of calculations. The furniture fire model provides the total burnrate and the mass fractions of soot and of other species constituents as an input to FAST for computations of the upper gas layer.

Possible interaction problems which included consistencies in units, coordinate systems, and the time-stepping scheme were resolved. Time-stepping was controlled in such a way to avoid instabilities, since the present furniture fire model relies on an explicit time integration scheme.

Extensive, but straightforward, reevaluation of Hottel's exchange areas were needed to incorporate the upper and lower gas volumes and to incorporate the room boundaries. Since all surface elements in the room were included, this gave rise to radiation blocking between the chair and the room. With the extra gas layers and the extra surface elements defined, the smoothing of Hottel's exchange areas to preserve energy conservation was severely tested. Its algorithm also was revised.

3.2 HEMFAST DATA INPUT DESCRIPTION

There are two input data files used by the HEMFAST model. The input data file is essentially in the format of Version 17 of the Transport of Fire, Smoke, and Toxic Gases (FAST) program and a description of the data file is given in the User's Guide (11). For the sample run, a rectangular room with a single window-opening to the outside was geometrically simulated. The conductive and emissivity properties in SI units were provided for the ceiling, wall, and floor. When the computer index variable, LFBT is set to 5, the type of fire simulated is the furniture fire. For LFBT other than five, the HEMFAST program reduces to the FAST program. Thus, the modularity of fire types is retained, although the program code may need further restructuring and inner documentation to make it more convenient to the user. Since the furniture fire model is a self-controllable fire source the value of LFMAX in input data file need not be greater than one. If the value of LFMAX is one, it can be used to define the time interval of fire growth in seconds and to initialize the mass fractions of the product gases of fuel mass combustion. These initial values of mass fractions were held constant throughout the fire growth if the corresponding bench scale data of the molecular constituents were not available as a function of time. The initial values of mass fractions of N_2 , CO_2 , CO , H_2O , and soot were taken to be that of a generic polyurethane (PU) foam.

The second input data file contains bench scale fire properties of a furniture material and the specifications for a four cushion chair or couch geometry. The furniture material selected for the test case was a 50mm thick, light olefin/California PU foam material (3). The bench scale data consisted of:

- a) - burn rate vs time
 - b) - mass loss rate vs time
 - c) - ignition temperature ($711^\circ K$) (Reference 12)
 - d) - thermal thickness ($0.72 \text{ KJ}/^\circ K m^2$) (Reference 12)
- { for $25 \text{ kW}/m^2$ irradiance of the
cone calorimeter (Reference 3)

- e) - horizontal flame spreading constant of the material
(Reference 12)
- f) - maximum soot volume fraction (0.89 PPM) (Reference 4)
- g) - flame temperature (1200°K) (Reference 4)

The furniture geometry simulated was the four-cushion furniture mockup similar to that shown in Krasny and Babrauskas (3). A simulated cushion was considered to be a 400 mm length panel with four surface elements. Four of the cushion panels were connected and arranged into a chair for the demonstration computer run. The user can control the chair geometry with the input data file. The last entries in the data file refer to additional input in the spark ignition at time "zero" and its location on the right-rear surface element of the seat panel.

3.3 HEMFAST DEMONSTRATION RESULTS

As indicated in the FAST User Guide, the first output data is a summary of input data. When the fire type is the furniture fire, the FAST output was changed so that the "Time Step" is now controlled by the user and "Number of Fire Intervals", "Effective Heat of Combustion", "FMASS", "FHIGH", and "FTIME" output parameters are ignored. In later editions of the code these types of outputs will be suppressed. At "Time = 0.0 seconds" the output variables of the calculations are initialized. Note that concentrations of N_2 and H_2O are initialized. The amount of water vapor assumed to exist in the lower gas layer corresponds to 50% relative humidity at a room temperature of 300°K. The next set of output is related to the description of the furniture surface elements located relative to the room origin (the right-rear corner of the room as shown in Figure 16). Each surface element's mid-point vector, area, and the normal vector are needed as inputs to the thermal radiation model of the furniture fire model.

At the first time increment, (10 seconds) the furniture fire sub-model computes a pool flame (centered at 2.2, 2.05, 0.5 meters) on the first surface element of the furniture with a base radius of

- 1 - 16 Chair
- 17 Ceiling
- 18 - 21 Upper Wall
- 22 - 25 Lower Wall
- 26 Floor

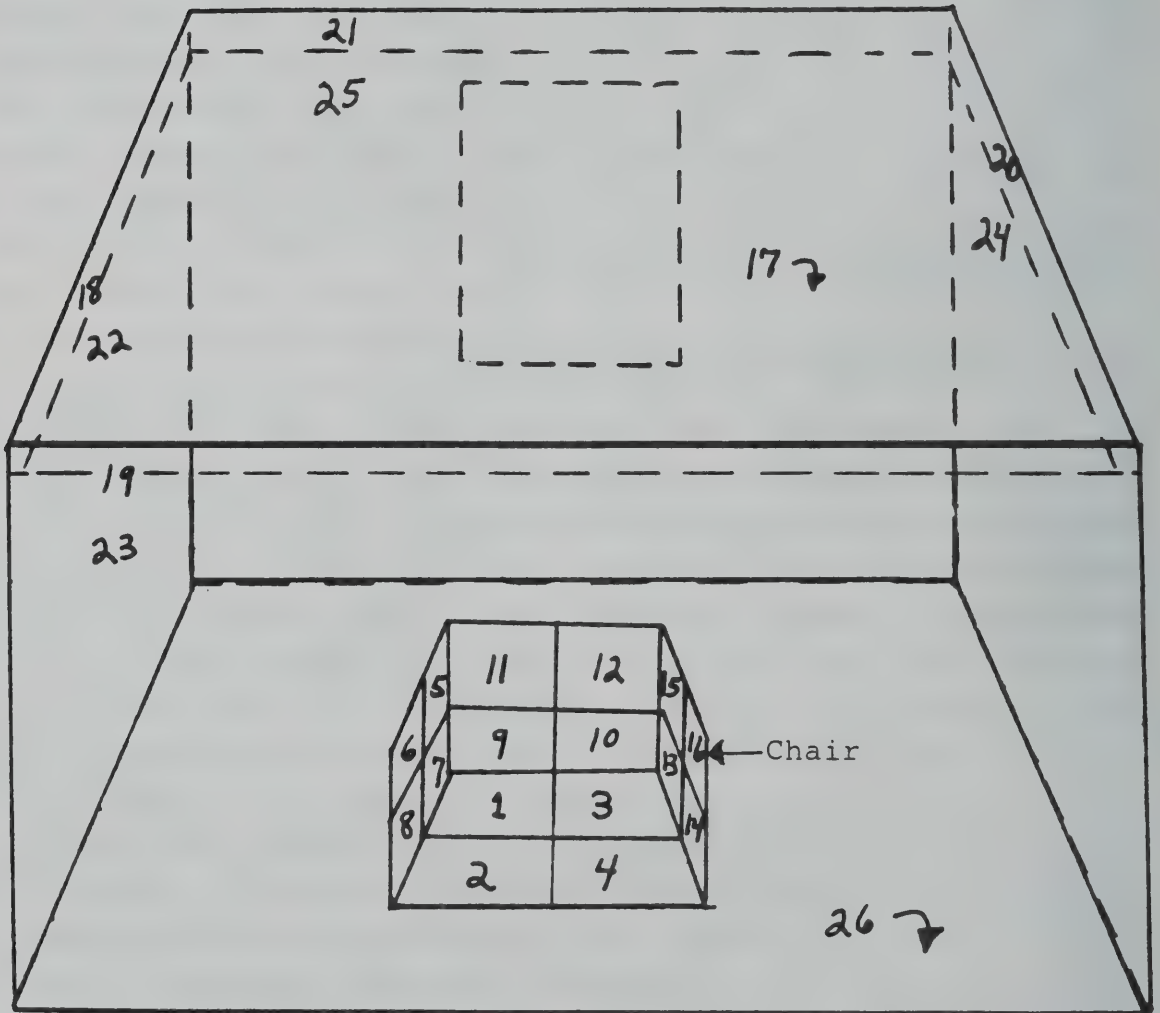


Fig. 16. Arrangement of Surface Elements on Chair and Room.

0.01 m, flame radiative height of 0.001 m, and a burnrate of 0.001 kW (see Figure 17). The result of the radiative heat transfer analysis provides interesting and reasonable features. Included in the printout are the three isothermal gas volumes, the pool flame, the upper gas layer, and the lower gas layer. Also included are all the surface elements of the furniture and of the room. The first volume element, the pool fire volume, has the following result: zero scattering, a small total fire area, small gray-body emissivity of 0.0027, a black-body power of 11.76 kW/m^2 , an irradiance of 0.472 kW/m^2 from the upper and lower gas volumes and all the surface elements, a radiance of 117.6 kW/m^2 , and a net radiative power loss of 0.00021 kW which was 21% of the burnrate. The small upper gas layer has a net radiative power gain of $0.11 \times 10^{-4} \text{ kW}$. The lower gas layer on the other hand has a large gray-body emissivity of 0.143 due to the large mean beam length and the presence of 50% relative humidity. It also has a large net radiative power gain (0.00056 kW) compared to the other elements. The only element with a higher net power gain (0.00058 kW) is Element 17, the ceiling.

The first surface element on the furniture contained the relatively small fire base, which resulted in a slightly higher overall surface emissivity of 0.8014. However, its overall radiance of 0.541 kW/m^2 was higher than the irradiance of 0.461 kW/m^2 , resulting in a net radiative power loss of 0.032 kW. This is much greater than the net power loss of the pool fire. This is not too surprising considering the small gray-body emissivity of the pancake shaped pool fire. To sustain the ignited surface element base at 711°K and a radiance of 0.0032 kW requires glowing combustion of the fabric/foam material. All the other surface elements should be absorbing net radiative power in relation to their view factors from the pool fire. This is generally the case, except for three insignificant surface elements. These exceptions are the result of either roundoff errors or an error tolerance of the Gauss-Siedel matrix solution not being small enough.

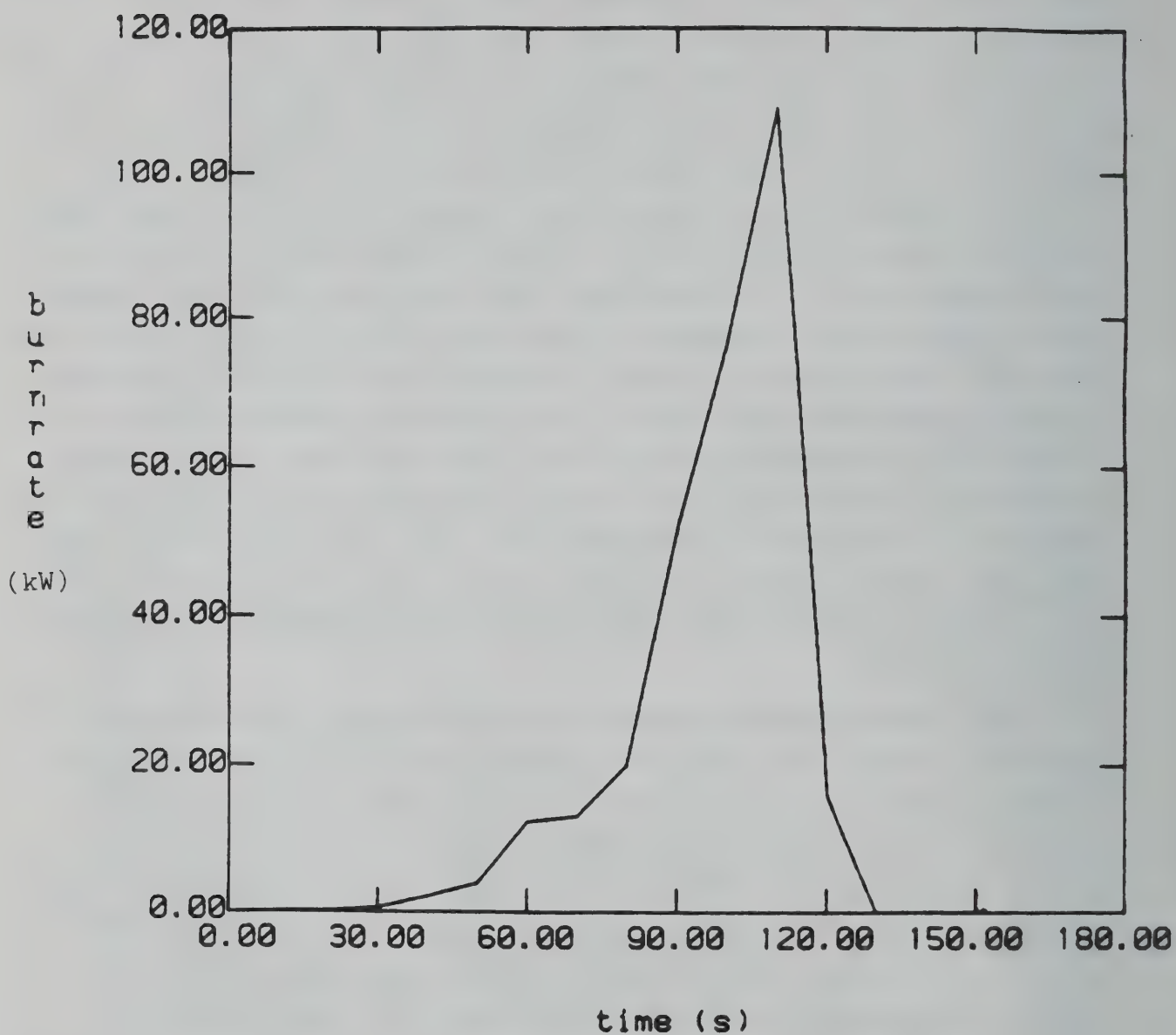


Fig. 17. HEMFAST Prediction of Burnrate in kW
versus Time for the Sample Chair Fire.

These overall results of the radiative heat transfer are unexpected of large pool fires, but they are essential to the early development of the furniture fire. For the rest of the simulation at time = 10 seconds, not much was changing in the other variables. All the temperatures were still at approximately 300°K (see Figure 18), except for the first furniture surface element midpoint, which was at ignition temperature of 711°K. The upper layer species concentrations of CO₂, CO, H₂O, OD and CT started at very low values (See Figure 19).

The HEMFAST results began to change in character by time = 40 seconds. The pool fire was then burning at a rate of 2.1 kW, as shown in Figure 17, the fire base radius was 0.09 m, and the flame radiative height was 0.05 m. The net radiative fraction of the pool fire burnrate has increased to 25% and the flame emissivity has increased to 0.05. The flame has a net radiative power loss of 0.51 kW, which at this time is greater than the net radiative power loss of 0.3 kW of the ignited surface element. The upper and lower gas layers were experiencing net radiative power loss instead of net power gain. This was due largely to the temperature of the upper and lower gas layers being 10°C greater than the temperature of the ceiling, walls, and floor (see Figure 18). The upper gas layer was 0.5 m deep with a temperature of 310.9°K. The parts per million concentration of CO₂, CO, and H₂O were 138, 6.0, and 780, respectively (see Figure 14). The soot opacity was 6×10^{-3} per meter. The armrest surface element adjacent to the burning seat element has its temperature at 324°K and the adjacent backrest surface element was at 321°K.

At time = 50 seconds, with a burnrate of 3.93 kW, the pool fire has spread over the adjacent surface elements on the armrest and backrest. As a result, the pool fire radiative height began to rapidly increase to 0.15 meters and the radiative fraction increased to 45% over the next 20 seconds. At 50 seconds, the pool fire has become the dominate radiation emitter at 1.23 kW and most burning surface elements still were experiencing net radiative power loss. At this point it is uncertain whether the burning

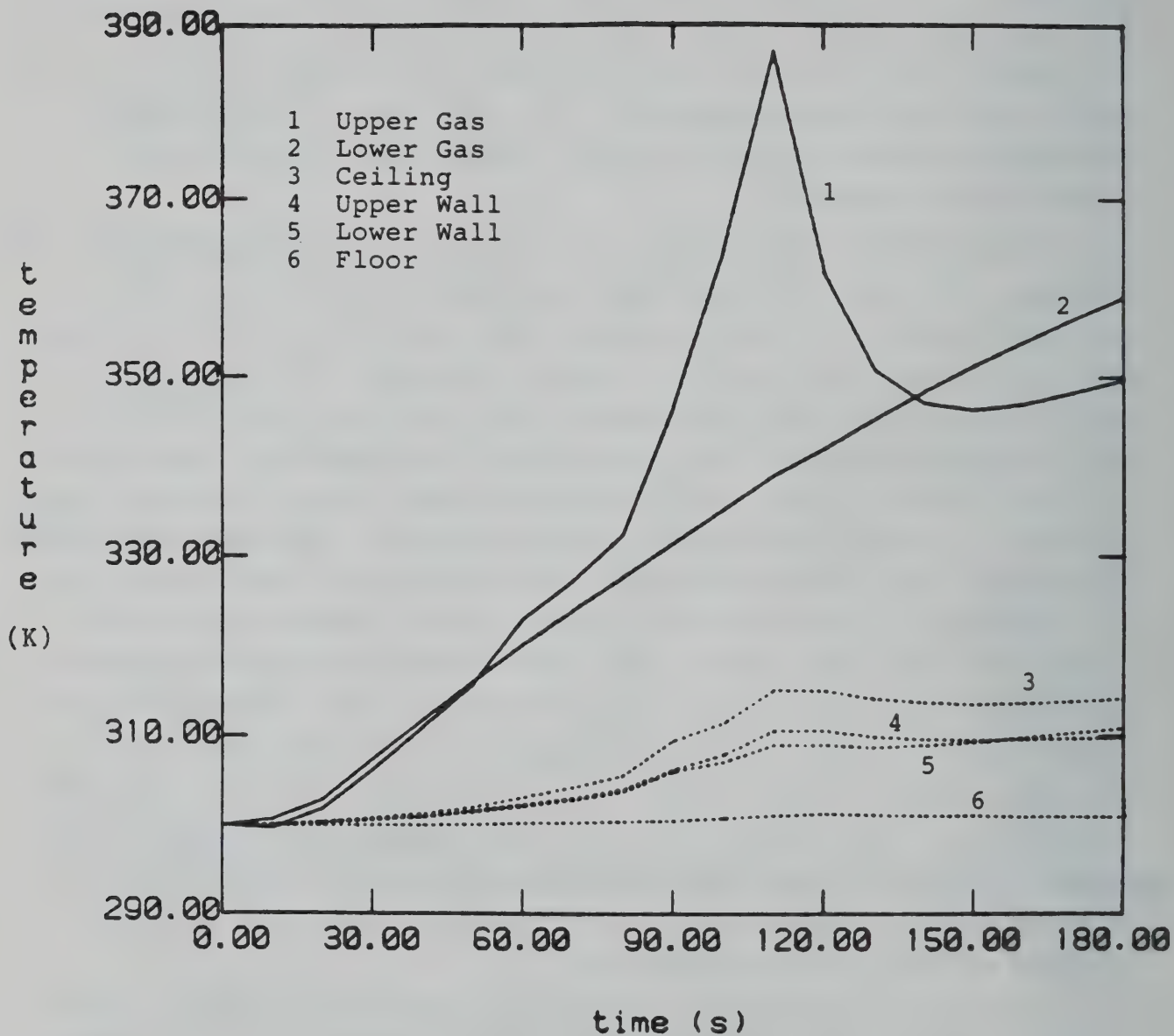


Fig. 18. HEMFAST Prediction of Temperatures of Upper Gas, Lower Gas, Ceiling, Upper Wall, Lower Wall, and Floor versus Time.

surface elements were sustained by glowing combustion (because convective heating was not yet directly calculated), nor was it certain the burning surface elements will remain at the ignition temperature of 711°K.

Indeed, at 70 seconds a small problem occurred when the temperature prediction of some virgin surface elements dropped significantly below 300°K. This may be related to: (1) a stability problem, thus requiring smaller time step; (2) not considering a wall fire as separate from the pool fire; or (3) more explicit use of convective heat transfer calculations may be needed. A numerical stabilizing influence occurs when the surface temperature was predicted to rise above the ignition temperature. This indicates spontaneous thermal ignition, which would happen with a more stable surface temperature prediction. The surface was then set at the ignition temperature, 711°K, and the burning rate initialized for that element. This, in fact, happened at time = 80 seconds on the left armrest and then at time = 90 seconds on the remaining surface elements on the backrest.

At time = 80 seconds, the burnrate was 20 kW, the whole seat and parts of the side and backrest were burning, the flame radiation height was 0.15 m, and the radiation fraction became 51% of the burnrate. With the flame emissivity approaching 0.18 with a radiative net power loss of 10.3 kW, some burning surface elements began to switch to net radiative power gain. This in turn enhanced the burning rate of the surface elements.

At 90 seconds, the burnrate was 52 kW, the flame radiation height became 0.3 m, and the whole mockup was on fire. The flame emissivity continued to increase up to 0.28 with radiative net power loss of 23.6 kW. At this point in time the fire was experiencing its greatest growth rate, that is, all the furniture surface elements had ignited and were burning. The flame spreading process has nearly finished and the continued fire growth is resulting from the increasing flame radiative heat feedback to the burning surfaces. Eventually, the fire growth reaches a limit dictated either by the flame soot volume fraction reaching its

maximum value for the given flame base radius or by the burnout of some surface elements.

Other calculated features of the furniture fire growth at 90 seconds are the following. The upper gas layer has reached a limiting depth of 0.7 m considering the open window. The temperature of the upper gas layer has reached 346.5°K, while the lower gas layer has reached 331.3°K mainly because of the radiant absorption by the water vapor. The ceiling, upper wall, lower wall, and floor temperatures were calculated as 309.4, 306.2, 306.0 and 300.5°K, respectively. The upper layer species concentration of CO₂, CO, and H₂O were 2976, 129, and 16960 ppm, respectively. The soot opacity was 0.227 per meter.

At 110 seconds, the simulated furniture burnrate finally reaches a peak of 109 kW. This gives a flame radiance height of 0.5 m and a flame gray emissivity of 0.326. The net radiant power loss was 40 kW for the flame, 2.6 kW for the upper gas layer, and -1.1 kW for the lower gas layer. It is interesting that the upper gas layer consistently had a net radiant energy loss to the lower gas layers and to all the walls despite the radiant heat gain from the furniture fire. Yet the upper gas layer was still heated by the convective heat portion of the furniture burning rate. This process gave the result of 387°K for the temperature of the upper gas layer with its depth still at 0.7 m. The calculated temperatures for the lower gas layer, ceiling, upper wall, lower wall, and the floor were 338.9°K, 315.1°K, 310.6°K, 309.0°K, and 301.1°K, respectively. The upper layer species concentration for CO₂, CO, and H₂O reached their peak values of 4997.0, 217.0, and 19640 ppm, respectively. There were a couple of furniture surface elements that burnt out, thus indicating a rapid downward trend of the furniture burning rate. By the time 130 seconds, the mockup was burnt out.

SECTION 4

CONCLUSIONS

HEMFAST is a computer program which simulates the furniture fire and the toxic gas growth in a room and its spread to the other rooms. This was achieved by incorporating the furniture fire model into the FAST model. The furniture fire model was designed to be self-controllable in simulating a fire source utilizing as inputs only the bench scale data of material burning rate, flame spreading, thermal ignition, and the flame properties of the following: soot volume fraction, CO_2 , H_2O mass fractions of fuel weight, and gas temperatures. The Froude modeling of flame shape and of uniform flame properties is utilized following McCaffrey (13) and Orloff and de Ris (6). To obtain the self-controllability in the furniture fire model, and also in HEMFAST, a practical 3-D thermal radiation model was used (14) in calculating the heat feedback from the flames to the flame front in the determination of the flame spread rates, and to the flame base in the determination of the local material burning rates. In the HEMFAST program, the thermal radiation model (14) was extended to include the upper and lower gas layers and the room enclosure. Since the Hottel's zoning method was used in the thermal radiation model it was possible to consider surface emissivities less than unity on all surfaces, and to consider three isothermal gray gas volumes which are the high-temperature flaming plume, the sooty upper gas layer, and the lower gas layer at 50% relative humidity.

Some salient features were noted in the simulation of a sample fire growth on a furniture mockup. Immediately after the seat was ignited, the pool fire was inferred to be sustained by glowing combustion within the burning material while the flame front was spreading at its slowest rate. This was shown by the relatively high net radiative power loss calculated for the burning material. The simulated furniture fire tended to grow at a low exponential rate for a slow but increasing flame spread rate from the octagonal flame base.

As the flame base reached the right armrest and the right side of the backrest, a new phase in the fire growth rate developed. This new phase is caused by the additional burnrate of the side walls and its radiative feedback to the burning seat. The increased burning rate led to a higher flame radiative height and also to a higher soot volume fraction. The final phase in the fire growth rate involved the spontaneous thermal ignition of the remaining surface elements. This phenomena has also been observed in VCR observations of mockup burning. During the first two phases of the fire growth, i.e., the seat and side wall flame spreading many of the burning surface elements had a net radiative power loss. Only after the spontaneous thermal ignition of several surface elements was the radiative feedback sufficient to the result in net radiative gain for these burning surface elements. With all the elements burning at this time, the fire growth was at its greatest. However, the peak in the furniture fire burnrate in this case was limited by the surface elements burnout as opposed to being limited by the maximum soot volume fraction for a given flame base size.

The upper and lower gas layers eventually rose 87 and 39°C respectively above the initial room temperature while the upper layer constituents for CO_2 , CO , H_2O eventually reached 4997, 217, and 19640 ppm respectively at peak burning rate. Throughout most of the fire growth, the upper layer had a net radiative heat loss to the lower gas layer and wall despite the heat gain from the furniture fire. Whether the upper gas layer will have a net radiative heat gain or loss depends on its geometry, soot volume fraction, and gas temperature in relation to other radiative sources.

SECTION 5

RECOMMENDATIONS

Although the HEMFAST program currently predicts the qualitative behavior of the furniture fire growth in a room, it will need some specific revisions for quantitative comparisons with the data, especially the data by Krasny and Babrauska (3). Also, the current version of HEMFAST is not user friendly; is not thoroughly debugged; does not yet incorporate all the features; and is not thoroughly optimized. It would be useful to somehow derive the flame properties of soot volume fraction, CO_2 , and H_2O mass fractions, and the gas temperatures within the flame from the bench scale data. Currently, these flame properties are from the data obtained by Pagni and Bard (4) for a PU foam. The bench scale data available on the horizontal and lateral flame spreading on furniture materials is very limited. At the present some data on the flame rate can only be inferred from the VCR observations of furniture mockup burnings (3). Also, for some cases, the data for the temperature of the burning surface is nonexistent. The HEMFAST model can be improved in the following areas: (1) the prediction of the furniture surface temperatures by using more stable numerical technique, such as the one used in the FAST model for the room wall temperatures; (2) insert an additional flame source by including a wall fire algorithm of existing integral models of wall fire; (3) perform a more in-depth processing of the bench-scale data on the burning rates of furniture materials as measured by the calorimeter to infer the burning surface temperature and scaling factor due to the different irradiances from the cone calorimeter; (4) do a thorough re-examination of the Hottel's exchange area approximations in the thermal radiation model especially regarding the conclusions about the importance of glowing combustion in the early phases of the furniture fire growth, and (5) the computer programming of HEMFAST can be improved to make it more user friendly, more modular, and more extensively documented. An area of documentation needed is in geometrical representation of the furniture and flame shapes by surface elements and of the flame

spreading regions by surface polygons. The role of three-dimensional vector analysis in deriving geometrical properties such as flame volume and areas as well as flame base size and area should be included in the documentation.

SECTION 6
REFERENCES

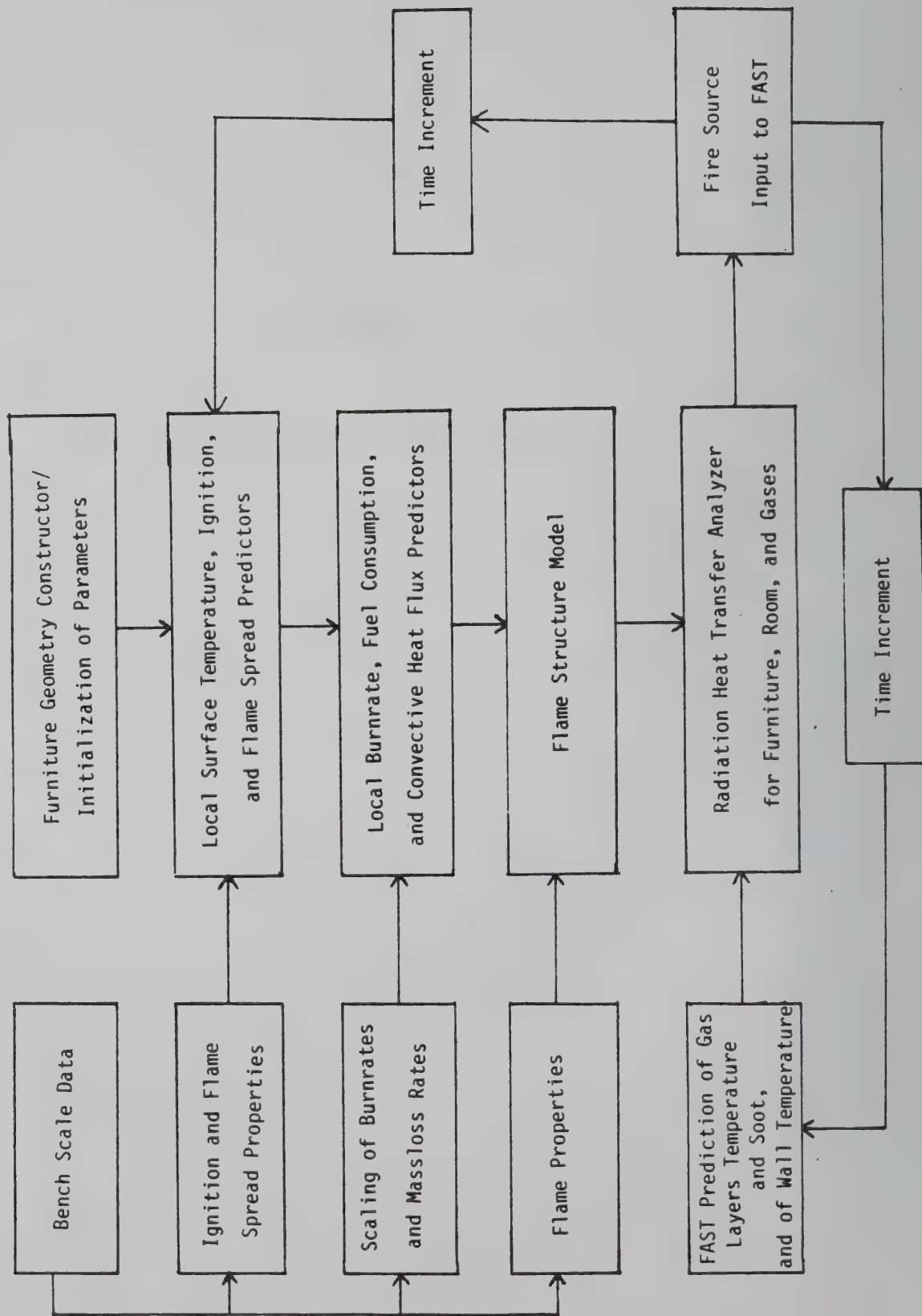
1. Dietenberger, M.A., Furniture Fire Model, NBS-GCR-84-480, November 1984.
2. Dietenberger, M.A., Mathematical Modeling of Furniture Fires, NBS-GCR-86-506, February 1986.
3. Krasny, J.F., and V. Babrauskas, "Burning Behavior of Upholstered Furniture Mockups," Journal of Fire Sciences, Vol. 2, May/June 1984, pp.205-235.
4. Pagni, P.M. and S. Bard, "Spatial Variation of Soot Volume Fractions in Pool Fire Diffusion Flames." Presented at First International Symposium on Fire Safety Science, National Bureau of Standards, Gaithersburg, Maryland, October 7-11, 1985.
5. Babrauskas, V., and J. Krasny, Fire Behavior of Upholstered Furniture, NBS Monograph 173, November 1985.
6. Orloff, L., and J. de Ris, "Froude Modeling of Pool Fires," Nineteenth Symposium (International) on Combustion, The Combustion Institute, p. 885, 1983.
7. Ahmad, T. and Faeth, G.M. "Turbulent Wall Fires" Colloquim on Fire and Explosion, 16th Symp. Comb. pp.1149-1160, 1978.
8. Cetegen, B.M., E.E. Zukowski, and T. Kubota, "Entrainment and Flame Geometry of Fire Plumes," California Institute of Technology, NBS Grant G8-9014, Aug. 1982
9. Hasemi, Y. "Thermal Modeling of Upward Wall Flame Spread" Fire Safety Science-Proceedings of the First International Symposium, pp. 87-96, Nov 1985.
10. Siegel, R. and T.R. Howell, Thermal Radiation Heat Transfer, 2nd Ed. Hemisphere Publishing Corporation, Washington, 1981.
11. Walton, W.D., S.R. Baer, and W.W. Jones, "User's Guide for FAST," NBSIR 85-3284, December 1985.
12. Dietenberger, M.A., "Utilization of Bench Scale Ignition and Flame Spread Measurements for Furniture Fire Model." Prepared for UJNR Panel on Fire Research and Safety, Tsukuba, Japan, May 1985.
13. McCaffrey, B.J., "Momentum Implications for Buoyant Diffusion Flames," Combustion and Flame, Vol. 32, pp. 149-167, 1983.

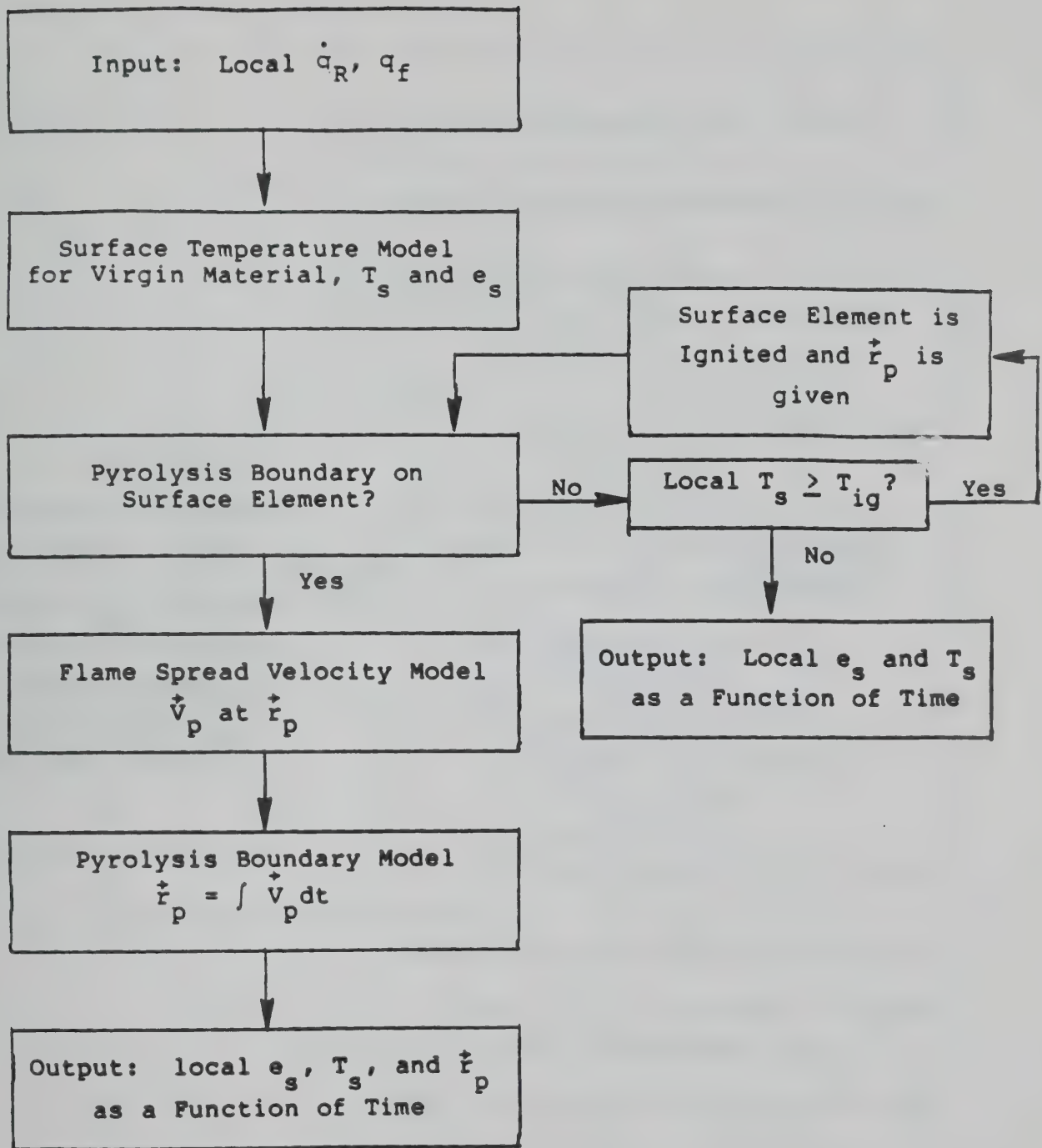
14. Dietenberger, M.A., "Practical Thermal Radiation Model for 3-D Gray Flames and Objects." Presented at Annual Conference of Fire Research at NBS, Gaithersburg, Maryland, October 1984.

APPENDIX A

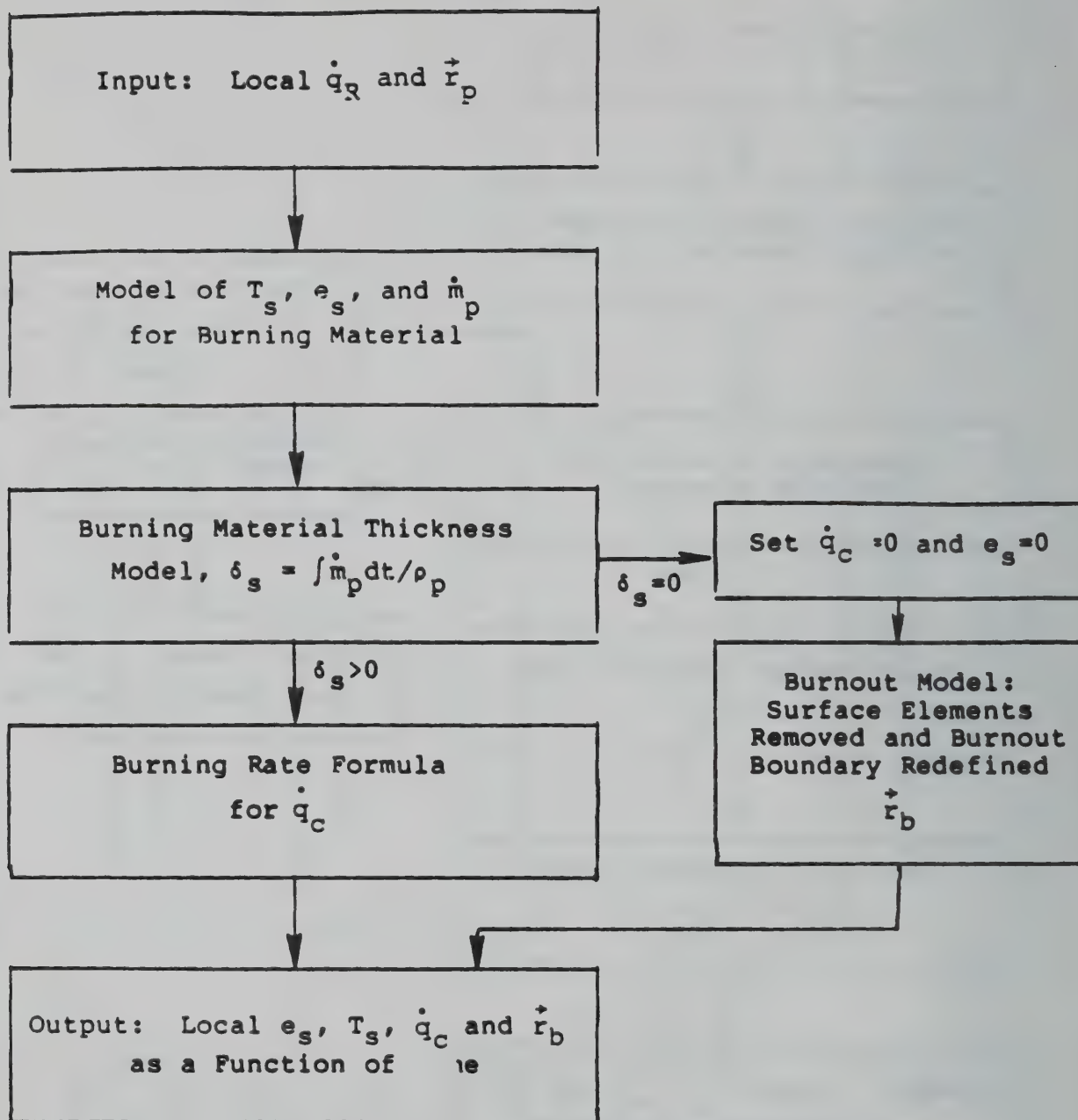
HIGH LEVEL FLOWCHARTS OF HEMFAST MODEL

Furniture Fire Modules and FAST (HEMFAST)

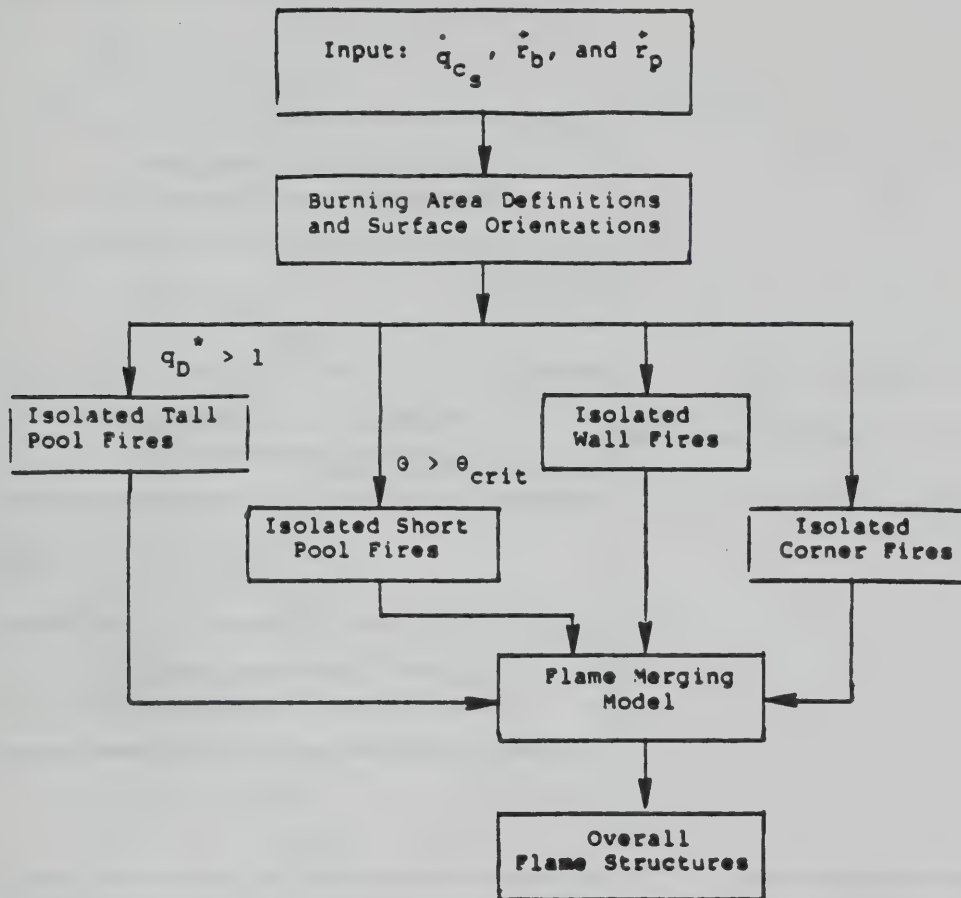




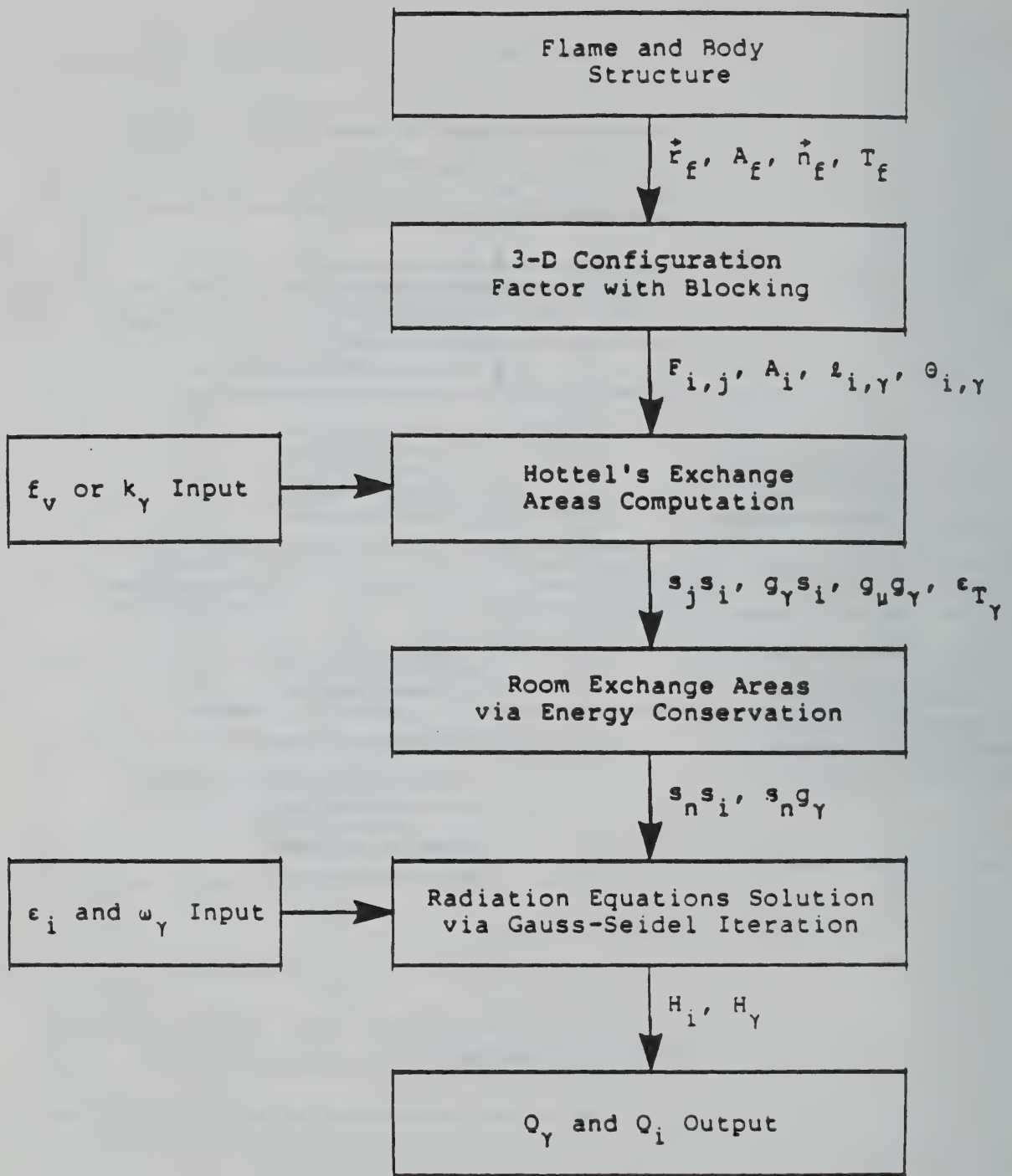
Local Surface Temperature Ignition, and Flame Spread Predictors



Local Burn Rate, Fuel Consumption, and Convective Heat Flux Predictors



Flame Structure Model



Thermal Radiation Heat Transfer Analyzer Module

APENDIX B

PROGRAMMER'S COMMENTS

PROGRAMMER'S COMMENTS:

The tape is written at 1600 BPI,
Block Size is 5120
Record size is 80 characters, fixed length
No carriage control

The tape contains three files:

1. The HEMFAST Program
2. Data file A (FAST.DAT)
3. Data file B (FURNITURE.DAT)

Data file A contains the data required by Version 17 of the
NBS FAST model

Data file B contains data required by the UD Furniture Fire
model

Data file A is read from FORTRAN Unit 001

Data file B is read from FORTRAN Unit 005

The output is written to FORTRAN Unit 006 (a sample output
is enclosed)

You will probably need to add two or three OPEN statements
at the beginning of the program to take care of this.

APPENDIX C

PRINTOUT OF HEMFAST RESULTS FOR
TEST CASE FURNITURE FIRE AT
SIMULATION TIME, 60 SECONDS

BUILDING XYZ

TOTAL COMPARTMENTS = 1
MAXIMUM OPENINGS PER PAIR = 1

FLOOR PLAN

WIDTH 4.6
DEPTH 4.3
HEIGHT 2.4
AREA 19.8
VOLUME 47.5
CEILING 2.4
FLOOR 0.0

CONNECTIONS

1 (1) BW= 0.0 1.3
HH= 0.0 2.1
HL= 0.0 0.6
HHP= 0.0 2.1
HLP= 0.0 0.6

CEILING

COND = 1.800E-04
SPHT = 9.000E-01
DNSTY= 7.900E+02
THICK= 1.600E-02
EMISS= 9.000E-01

FLOOR

COND = 1.700E-03
SPHT = 1.000E+00
DNSTY= 2.200E+03
THICK= 1.500E-01
EMISS= 9.000E-01

UPPER WALL

COND = 1.800E-04
SPHT = 9.000E-01
DNSTY= 7.900E+02
THICK= 1.600E-02
EMISS= 9.000E-01

LOWER WALL

COND = 1.800E-04
SPHT = 9.000E-01
DNSTY= 7.900E+02
THICK= 1.600E-02
EMISS= 9.000E-01

FIRE ROOM NUMBER IS 1
TIME STEP IS 10.00 SECONDS
PRINT EVERY 1 TIME STEPS
NUMBER OF FIRE INTERVALS = 1

TOTAL TIME INTERVAL = 18
FIRE SOURCE = 1
FIRE TYPE = FURNITRE FIRE

INITIAL FUEL TEMPERATURE (K) = 300.
AMBIENT AIR TEMPERATURE (K) = 300.
AMBIENT REFERENCE PRESSURE (kPa) = 101.30
EFFECTIVE HEAT OF COMBUSTION (KJ/KG) = 18000.

FMASS= 0.00E+00 0.00E+00
FHIGH= 0.00E+00 0.00E+00
N2= 7.1 0.00E+00
CO2= 2.2 0.00E+00
CO= 6.00E-02 0.00E+00
H2O= 0.67 0.00E+00
OD= 2.00E-02 0.00E+00
CT= 1.0 0.00E+00
FTIME= 10.

CONFIG FILE =

FURNITURE BURNRATE IS 12.36035 KW AT TIME 60.00000 SEC
SMFAC < 0.5 IN RMTERM SUBROUTINE MEANS A 0.3953227
RELATIVE CHANGE IN THE SUM OF SURFACE-GAS EXCHANGE AREAS
PROVIDED THE SUM OF GAS-GAS EXCHANGE AREAS ARE CORRECT;
THE SUMS WERE FOR THE GAS VOLUME # 1

RESULT OF RADIATIVE HEAT TRANSFER ANALYSIS FOR THE NEXT TIME INCREMENT AT FIRE
SOURCE ROOM

THE VAPOR PRESSURE FOR CO2 FOR LOWER AND UPPER GASES AND FOR H2O FOR LOWER AND
UPPER GASES ARE 0.0000000E+00 2.3781539E-04 1.5071809E-02 1.0837992E-02

ITERATION FLAME AREA RAD. FRACTION FLAME HEIGHT FLAME RADIUS
4 0.2683476 -0.3345792 0.1523599 0.1289839

ELE	SCAT/COSAV	ELEM. AREA	EMISSIVITY	BLCKBDYPOW	IRRADIANCE	RADIANCE	NETPOWER (KW)
1	0.0000E+00	0.2683E+00	0.1341E+00	0.1176E+03	0.2640E+01	0.1176E+03	-0.4136E+01
2	0.0000E+00	0.4924E+02	0.8132E-01	0.5627E+00	0.5357E+00	0.5627E+00	-0.1081E+00
3	0.0000E+00	0.7416E+02	0.1271E+00	0.5648E+00	0.5350E+00	0.5648E+00	-0.2811E+00
1	0.1000E+01	0.4000E-01	0.1000E+01	0.1451E+02	0.1170E+02	0.1451E+02	-0.1125E+00
2	0.7223E+00	0.4000E-01	0.8000E+00	0.1860E+01	0.3381E+01	0.2164E+01	0.4865E-01
3	0.7239E+00	0.4000E-01	0.8000E+00	0.1954E+01	0.3897E+01	0.2342E+01	0.6218E-01
4	0.4525E+00	0.4000E-01	0.8000E+00	0.1348E+01	0.3719E+01	0.1822E+01	0.7589E-01
5	0.5550E+00	0.4000E-01	0.1000E+01	0.1451E+02	0.6337E+01	0.1451E+02	-0.3271E+00
6	0.4540E+00	0.4000E-01	0.8000E+00	0.1777E+01	0.4268E+01	0.2275E+01	0.7973E-01
7	0.2262E-01	0.4000E-01	0.1000E+01	0.1451E+02	0.7015E+01	0.1451E+02	-0.3000E+00
8	0.6487E+00	0.4000E-01	0.8000E+00	0.2218E+01	0.5904E+01	0.2955E+01	0.1179E+00
9	0.1000E+01	0.4000E-01	0.1000E+01	0.1451E+02	0.1214E+02	0.1451E+02	-0.9495E-01
10	0.6542E+00	0.4000E-01	0.8000E+00	0.1691E+01	0.5586E+01	0.2470E+01	0.1246E+00
11	0.5496E+00	0.4000E-01	0.1000E+01	0.1451E+02	0.5406E+01	0.1451E+02	-0.3643E+00
12	0.4553E+00	0.4000E-01	0.8000E+00	0.1362E+01	0.3890E+01	0.1867E+01	0.8089E-01
13	0.9262E+00	0.4000E-01	0.8000E+00	0.7332E+01	0.6400E+01	0.7145E+01	-0.2983E-01
14	0.8090E+00	0.4000E-01	0.8000E+00	0.5880E+01	0.5631E+01	0.5830E+01	-0.7952E-01
15	0.7512E+00	0.4000E-01	0.8000E+00	0.6992E+01	0.5532E+01	0.6700E+01	-0.4669E-01
16	0.6751E+00	0.4000E-01	0.8000E+00	0.6262E+01	0.5099E+01	0.6030E+01	-0.3722E-01
17	0.9903E+00	0.1978E+02	0.8000E+00	0.4718E+00	0.5323E+00	0.4839E+00	0.9580E+00
18	0.7818E+00	0.2338E+01	0.8000E+00	0.4688E+00	0.5253E+00	0.4801E+00	0.1057E+00
19	0.7968E+00	0.2501E+01	0.8000E+00	0.4688E+00	0.5471E+00	0.4845E+00	0.1567E+00
20	0.0000E+00	0.2338E+01	0.8000E+00	0.4688E+00	0.5326E+00	0.4816E+00	0.1194E+00
21	0.8006E+00	0.2501E+01	0.8000E+00	0.4688E+00	0.5029E+00	0.4756E+00	0.6814E-01
22	0.9829E+00	0.7982E+01	0.8000E+00	0.4683E+00	0.5143E+00	0.4775E+00	0.2936E+00
23	0.9796E+00	0.8539E+01	0.8000E+00	0.4683E+00	0.5682E+00	0.4883E+00	0.6827E+00
24	0.0000E+00	0.7982E+01	0.8000E+00	0.4683E+00	0.4972E+00	0.4741E+00	0.1844E+00
25	0.9796E+00	0.8539E+01	0.8000E+00	0.4683E+00	0.5157E+00	0.4778E+00	0.3240E+00
26	0.8989E+00	0.1978E+02	0.8000E+00	0.4597E+00	0.6074E+00	0.4893E+00	0.2336E+00

POWER IN KW ABSORBED BY ALL SURFACES IS 4.498150

TIME = 60.0 SECONDS.

U. TEMP. 322.8
L. TEMP. 320.0
U. VOLUM 11.9
U. DEPTH 0.6
CE. TEMP 303.1
UW. TEMP 302.3
LW. TEMP 302.1
FL. TEMP 300.2
EMS(I)= 6.066E-01
EMP(I)= 5.455E-04
QFC(I)= 8.225E+00
0.000E+00
QR(I)= -8.114E-01
-1.405E+00
QC(I)= -6.551E+00
-4.883E+00
Pres(kpa) -7.767E+00

Upper layer species concentration

N2 MASS : 2.61
PPM : 1.894E+05

CO2 MASS : 1.330E-02
PPM : 614.

CO MASS : 3.678E-04
PPM : 26.7

H2O MASS : 0.105
PPM : 1.190E+04

OD MASS : 1.316E-04
1/M : 3.874E-02

CT mg-m/l : 0.155

URNITURE FIRE SPREADING INFORMATION

PANEL # IS 1, # OF POLYGONS IS 1

PRINT FIRE SPREAD VECTORS, MAGNITUDES, AND STATUS

2.395982	2.050000	0.5000000	0.1959823	0
2.313682	2.163682	0.5000000	0.1607716	0
2.200000	2.246023	0.5000000	0.1960234	0
2.100000	2.148622	0.5000000	0.1405170	3
2.100000	1.952810	0.5000000	0.1397684	3
2.150000	1.951405	0.5000000	0.1198841	0
2.200000	1.950000	0.5000000	9.9999860E-02	2
2.296798	1.950000	0.5000000	0.1396075	2
2.395982	2.050000	0.5000000	0.1959823	0

PANEL # IS 2, # OF POLYGONS IS 1

PRINT FIRE SPREAD VECTORS, MAGNITUDES, AND STATUS

2. 200000	1. 950000	0. 5000000	0. 0000000E+00	1
2. 200000	1. 950000	0. 7000000	0. 2000000	0
2. 200000	1. 950000	0. 9000000	0. 4000000	-1
2. 296798	1. 950000	0. 9000000	0. 4000000	-1
2. 296798	1. 950000	0. 7000000	0. 2000000	0
2. 296798	1. 950000	0. 5000000	0. 0000000E+00	1
2. 200000	1. 950000	0. 5000000	0. 0000000E+00	1

PANEL # IS 3, # OF POLYGONS IS 1
 PRINT FIRE SPREAD VECTORS, MAGNITUDES, AND STATUS

2. 100000	1. 952810	0. 5000000	0. 0000000E+00	1
2. 100000	2. 148622	0. 5000000	0. 0000000E+00	1
2. 100000	2. 148622	0. 7000000	0. 2000000	0
2. 100000	2. 148622	0. 9000000	0. 4000000	-3
2. 100000	1. 952810	0. 9000000	0. 4000000	-3
2. 100000	1. 952810	0. 7000000	0. 2000000	0
2. 100000	1. 952810	0. 5000000	0. 0000000E+00	1

PRINTING OF ELEMENT STATUS, TEMPERATURE (K), BURNTIME (S), AND BURNRATE (KW)

1	1	711. 3000	45. 17346	3. 231312
2	0	425. 6111	0. 0000000E+00	0. 0000000E+00
3	0	430. 8394	0. 0000000E+00	0. 0000000E+00
4	0	392. 6586	0. 0000000E+00	0. 0000000E+00
5	1	711. 3000	20. 79620	2. 442346
6	0	420. 7428	0. 0000000E+00	0. 0000000E+00
7	1	711. 3000	21. 57066	2. 640063
8	0	444. 7470	0. 0000000E+00	0. 0000000E+00
9	1	711. 3000	21. 44027	2. 607153
10	0	415. 5579	0. 0000000E+00	0. 0000000E+00
11	1	711. 3000	20. 74713	2. 429640
12	0	393. 6865	0. 0000000E+00	0. 0000000E+00
13	0	599. 6725	0. 0000000E+00	0. 0000000E+00
14	0	567. 4828	0. 0000000E+00	0. 0000000E+00
15	0	592. 5883	0. 0000000E+00	0. 0000000E+00
16	0	576. 4911	0. 0000000E+00	0. 0000000E+00

FURNITURE BURNRATE IS 13.09751 KW AT TIME 70.00000 SEC

SMFAC < 0. 5 IN RMTERM SUBROUTINE MEANS A 0. 3739495

RELATIVE CHANGE IN THE SUM OF SURFACE-GAS EXCHANGE AREAS

PROVIDED THE SUM OF GAS-GAS EXCHANGE AREAS ARE CORRECT;

THE SUMS WERE FOR THE GAS VOLUME # 1

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBS/GCR-87/527	2. Performing Organ. Report No.	3. Publication Date March 1987
4. TITLE AND SUBTITLE DESCRIPTION AND RESULTS OF FURNITURE FIRE MODULES WITHIN FAST (HEMFAST)			
5. AUTHOR(S) Mark Dietenberger			
6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions) University of Dayton Research Inst. Analytical and Experimental Systems Group Structural Integrity Division Dayton, OH		7. Contract/Grant No. 60NANBSD0557 8. Type of Report & Period Covered Interim Tech. Rpt. 6/1/85 to 6/1/86	
9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP) National Bureau of Standards U.S. Department of Commerce Gaithersburg, MD 20899			
10. SUPPLEMENTARY NOTES ☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.			
11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here) The Heat and Mass Transport of Furniture Fire, Smoke and Toxic Gases (HEMFAST) program simulated the furniture fire and the toxic gas growth in a room and its spread to the other rooms. This was achieved by incorporating an improved furniture fire model into the FAST model in current usage at NBS> The furniture fire model was designed to be self-controllable in simulating a fire source utilizing as inputs only the bench scale data of new scalable material burning rates, flame spreading, thermal ignition, and the flame properties of the following: soot volume fraction, CO ₂ and H ₂ O mass fractions of fuel weight, and gas temperatures. Since the Hottels' zoning method was used in the thermal radiation model it was possible to consider surface emissivities less than unity on all surface elements, and to consider three isothermal gray gas volumes which are the high-temperature flaming plume, the sooty upper gas layer, and the lower gas layer at 50% relative humidity. Some salient features are noted in the simulation of a sample fire growth on a furniture mockup.			
12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons) computer programs; fire models; furniture; smoke; toxic gases; zone models			
13. AVAILABILITY ☒ Unlimited ☐ For Official Distribution. Do Not Release to NTIS ☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402. ☒ Order From National Technical Information Service (NTIS), Springfield, VA 22161		14. NO. OF PRINTED PAGES 15. Price	

